EU Legislation on WEEE Recycling and its Failure to Close The Loop of Critical Raw Materials

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Tiivistelmä - Referat – Abstract

E-waste (WEEE) is a significant source of Critical Raw Materials, which are materials that EU has deemed to be extremely important for its industry and at risk of supply disruption. However, the recycling rate from WEEE for most of these materials is very low, which is in direct contradiction to EU’s Circular Economy goals and industrial strategy. The goal of this thesis is to identify the shortcomings of EU WEEE legislation in promoting the circular use of CRMs, and then pinpoint the most critical issues that the legislation should pay attention to in order to improve the situation. The method used in the work is regulatory theory. The thesis finds that the current WEEE legislation is based around the previous generation of waste management issues, e.g. landfill capacity concerns, and does not take into account properly the current challenges of material efficiency and circularity. Improving the recycling rate of CRMs will require targeted legislative and policy action in key parts of the life cycle of electronics.

Sähkö- ja elektroniikkaromu (SER) sisältää huomattavia määriä kriittisiä raaka-aineita. Kriittiset raaka-aineet ovat raaka-aineita jotka EU on määritellyt elintärkeäksi teollisuudelleen ja joihin samanaikaisesti liittyy merkittäviä saatavuusriskejä. Tällä hetkellä kriittisten raaka-aineiden kierrätysaste SER:istä on erittäin matala, mikä on EU:n kiertotaloustavoitteiden sekä teollisuusstrategian vastaista. Tämän tutkielman päämäärä on tutkia miten ja miksi EU:n SER-lainsäädäntö on epäonnistunut kriittisten raaka-aineiden kierrätyksen suhteen sekä arvioida sitä, mihin asioihin lainsäädäntöuudistuksissa tulisi kiinnittää huomiota tilanteen parantamiseksi. Tutkielman metodina on sääntelyteoreettinen tutkimus. Tutkielman johtopäätös on että nykyinen SER-lainsäädäntö on rakennettu vanhempien jätehuollon ongelmien, kuten kaatopaikkajätteen määrän vähentämisen ympärille, eikä se ota riittävässä määrin huomioon tämänhetkisiä materiaalitehokkuuden ja kiertotalouden haasteita. Tilanteen parantaminen edellyttää elektroniikan elinkaaren avainkohtiin kohdistuvaa sääntelyä.

Avainsanat – Nyckelord – Keywords
e-waste, waste electrical & electronic equipment, critical raw materials, european union, recycling, circular economy, regulatory theory, SER, sähkö- ja elektroniikkaromu, kriittiset raaka-aineet, euroopan unioni, kierrätys, kiertotalous, sääntelyteoria

Säilytyspaikka – Förvaringställe – Where deposited
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Muita tietoja – Övriga uppgifter – Additional information

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Abbreviations

CRM	Critical Raw Material(s)
EOL	End-Of-Life
EOL-RIR	End-Of-Life Recycling Input Rate
EOL-RR	End-Of-Life Recycling Rate
EPR	Extended Producer Responsibility
EU	European Union
PWB	Printed Wiring Board
REE	Rare Earth Element (LREE: Light-, HREE: Heavy-)
WEEE	Waste Electronical & Electric Equipment

1. Introduction

1.1 Introduction to the subject

Waste electrical and electronic equipment (WEEE), such as computers, TV-sets, fridges and cell phones, is one the fastest growing waste streams in the EU, with some 9 million tonnes generated in 2005, and it is expected to grow to more than 12 million tonnes by 2020.[1] On a global scale, all countries in the world combined generated 44.7 million metric tonnes of e-waste annually in 2016, an equivalent of 6.1 kilograms per inhabitant, compared to the 5.8 kg/inh generated in 2014. The amount of e-waste globally is expected to increase to 52.2 million metric tonnes, or 6.8 kg/inh, by 2021.[2] While there has been significant improvements in the material recovery rates of WEEE during the last decades, the present growth is not enough to offset the growing stream of electronic waste.[3]

EU has identified materials that it calls "Critical Raw Materials" (CRMs) which are both economically very important for the Community and its industry, and at the same time at a risk of supply disruption[4] and in certain cases their extraction also causes significant environmental impacts.[5] These materials are heavily used in electronic technology.[6] The

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[1] European Commission, Waste Electrical & Electronic Equipment (WEEE) <https://ec.europa.eu/environment/waste/weee/index_en.htm> (Accessed 13.2.2020).

[2] Baldé, C.P., Forti V., Gray, V., Kuehr, R., Stegmann,P., The Global E-waste Monitor – 2017 (United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna). <https://www.itu.int/en/ITU-D/Climate-Change/Documents/GEM%202017/Global-E-waste%20Monitor%202017%20.pdf> (Accessed 12.1.2020).

[3] Idiano D'Adamo; Paolo Rosa; Sergio Terzi, "Challenges in Waste Electrical and Electronic Equipment Management: A Profitability Assessment in Three European Countries". Sustainability 2016, 8(7), 633; https://doi.org/10.3390/su8070633.

[4] Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Peirò, L.T., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., Ciupagea, C., "EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements", Resour. Policy 53, 12–19, 2017. doi:10.1016/j.resourpol.2017.05.008, and Communication from the Commission on the 2017 list of Critical Raw Materials for the EU [2017]. COM (2017) 490 final.

[5] Section 3.2.1.

[6] Mathieux, F., Ardente, F. , Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D. , Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. and Solar, S., *Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report* (EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017), p. 39.

current very low rate of recycling of these materials means that significant economic opportunities are lost and their mining causes environmental damage across the globe. The EU has stated that increasing the recovery of CRMs is one of the challenges that must be solved on the road towards a circular economy.[7] Rare earth elements (REEs, a subcategory of CRMs) recycling also has potential for significant positive environmental effects and reducing human health risks.[8]

Increasing the recovery of the materials present in electronic waste has significant potential for positive environmental impact, as the processes involved in harvesting virgin precious metals are environmentally costly. Mining requires considerable amount of land and creates waste water and sulfur dioxide emissions. Also, high amounts of CO_2 are generated and the refining operations use immense amount of electricity.[9] In contrast, recovery and recycling processes for the same metals from WEEE eliminate land use, waste water and sulfur dioxide emissions, while CO_2 emissions and energy consumption are cut down significantly.[10] Increasing the recycling rate of CRMs would also increase EU's self-sufficiency in those important elements. In addition, increasing the supply of secondary materials through

[7] Communication from the Commission on Closing the loop - An EU action plan for the Circular Economy [2015], COM/2015/0614 final. Also, European Commission, Directorate-General for Environment, *LIFE & the Circular economy* (Publications Office of the European Union, 2017), p. 81.
[8] For example: "REE [rare earth elements] recycling has significant advantages over the mining of rare earths including savings in energy, water and chemicals consumption, along with a significant reduction of emissions, effluents and solid waste generation resulting from the extraction and processing of rare earth ores. REE recyclates do not contain radioactive thorium and uranium, unlike the primary mined rare-earth ores. Therefore, radioactive tailing stockpiles and mining health problems can be, at least partially, avoided." Directorate General for Internal Policies, *Recovery of Rare Earths from Electronic wastes: An opportunity for High-Tech SMEs*, p .24. <https://www.europarl.europa.eu/RegData/etudes/STUD/2015/518777/IPOL_STU(2015)518777_EN.pdf> (Accessed 28.2.2020). The environmental and economical aspects are discussed in more detail in section 3.1.1.
[9] Christina Meskers, Christian Hagelüken, "Closed loop WEEE recycling? Challenges and opportunities for a global recycling society" in *Proceedings of sessions and symposia sponsored by the Extraction & Processing Division (EPD) of The Minerals, Metals & Materials Society (TMS)*, 2009. p. 1051.
[10] *Ibid*: "With "state-of-the-art" recovery processes, the "CO_2 emissions associated with the recovery of 75000 tons of precious, special and base metals from 300 000 t of recyclables and smelter by-products is only 0.28 Mt (3.73 t CO_2/t metal). Primary production of these metals would have generated 1.28 Mt CO_2 (17.1 t CO2/t metal)." Also see: European Parliament Briefing, Understanding waste streams. 2015, p. 4. <http://www.europarl.europa.eu/EPRS/EPRS-Briefing-564398-Understanding-waste-streams-FINAL.pdf> (Accessed 18.1.2020): "[R]ecycling other non-ferrous metals enables cost savings as well as energy savings ranging from 20% to 90%."

recycling is an important part of the EU raw materials initiative[11], circular economy action plan[12] and new industrial strategy[13].

Overall the recycling input rates (EOL-RIR) of CRMs is low, as seen in the table below. Only some of precious metals (gold, platinum group metals) are recovered and returned to the economy with any significant rates.

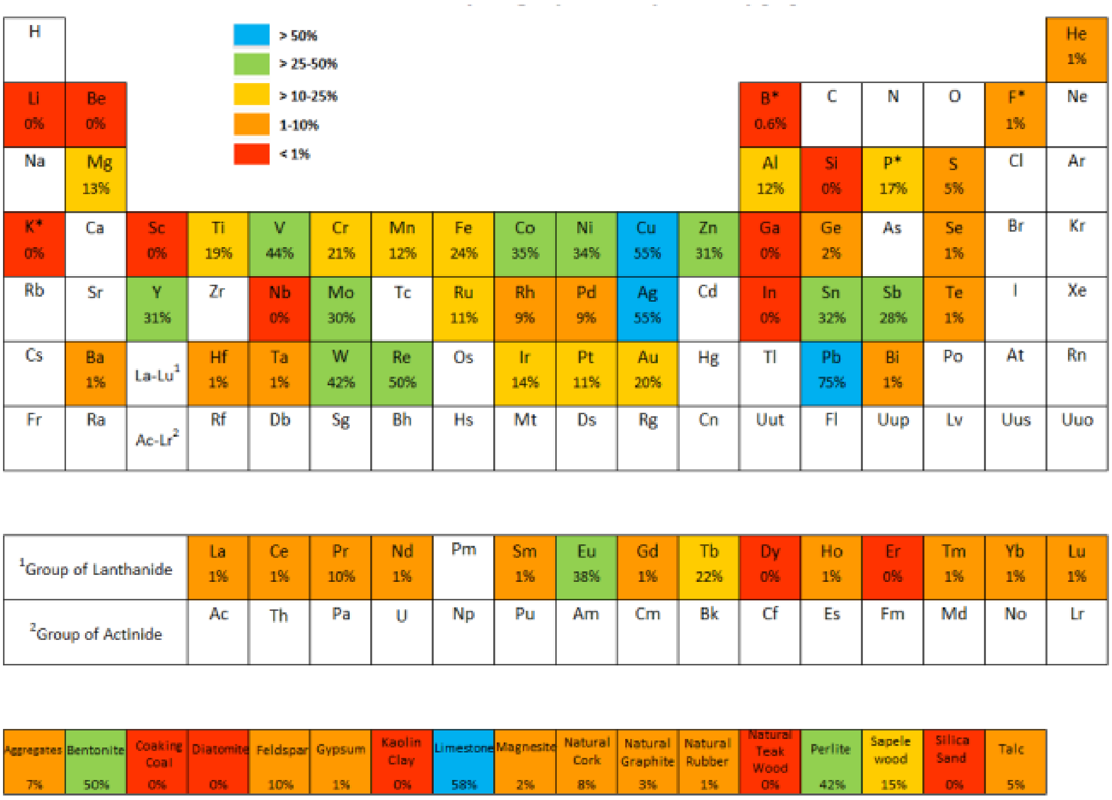

Figure 1: End-of-life recycling input rates of CRMs.[14]

[11] Communication from the Commission on the raw materials initiative — meeting our critical needs for growth and jobs in Europe [2008], COM(2008) 699 final, p. 3-4 and Communication from the Commission on Tackling the challenges in commodity markets and on raw materials [2011], COM(2011) 25 final, p. 12.
[12] COM(2015) 614 final, p. 16. "[I]ncreasing the recovery of critical raw materials is one of the challenges that must be addressed in the move to a more circular economy."
[13] Communication from the Commission on A New Industrial Strategy for Europe [2020], COM(2020) 102 final: "[W]e must move away from the age-old model of taking from the ground to make products, which we then use and throw away. We need to revolutionise the way we design, make, use and get rid of things by incentivising our industry."
[14] JRC 2017, p. 17, End-of-life recycling input rate measures what percentage of demand for the material is met by recycling (how much virgin raw material is replaced by recyclates in new products). Recycling rate measures the percentage of disposed material that is recovered.

In addition, end-of-life recycling rates (EOL-RR, which is a different metric than EOL-RIR, see cite note 14) for most CRMs from WEEE are 1 % or less[15]. This means that currently, the CRMs are being used in *linear economy* fashion, meaning that the materials are harvested, used in a product, and after the product has been discarded by its owner, the materials effectively disappear from the economy. All material used in this way must therefore be replaced by the mining of virgin raw materials. Meanwhile, the EU has set ambitious targets towards achieving Circular Economy, starting with a Circular Economy Package in 2015[16] and continuing with the more recent "Green Deal"[17]. In Circular Economy the goal is, inter alia, material efficiency, sustainable consumption and minimizing the loss of materials from the economy.[18] The current state of CRM recycling is in direct opposition of Circular Economy goals, and also against EU's Critical Raw Material strategy.[19] The problem has been noted by some recycling industry actors at least since 2008 (even before the revision of WEEE Directive, which was done in 2012)[20], but so far the EU has not reacted to these suggestions.

1.2. The research question

The main research question of this thesis is how and why the current EU legislation on WEEE does not facilitate the recycling of CRMs. I investigate the current legislation of the EU on electronic waste to identify the legislative bottlenecks that hinder the progress towards

[15]UNEP (2011) Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Graedel, T.E.; Allwood, J.; Birat, J.P.; Reck, B.K.; Sibley, S.F.; Sonnemann, G.; Buchert, M.; Hagelüken, C., p. 19. and JRC 2017, Annex I.
[16] COM/2015/0614 final.
[17] Communication from the Commission on The European Green Deal [2019], COM(2019) 640 final.

[18] See for example European Commission, "EU Circular Economy Action Plan" < https://ec.europa.eu/environment/circular-economy/> (Accessed 10.5.2020). Further, see section 2.2.
[19] Communication from the Commission on the 2017 list of Critical Raw Materials for the EU [2017], COM(2017) 490 final, p. 2-3. "Raw materials, even if not classed as critical, are important for the European economy as they are at the beginning of manufacturing value chains. Their availability may quickly change in line with trade flows or trade policy developments underlining the general need of diversification of supply and the increase of recycling rates of all raw materials."
[20] C. Hagelüken, C. E. M. Meskers, "Mining our computers – opportunities and challenges to recover scarce and valuable metals from end-of-life electronic devices" in H. Reichl, N. Nissen, J. Muller, & O. Deubzer, (eds) *Electronics Goes Green 2008+* (Berlin: Fraunhofer IRB Verlag, 2008), p. 623. In addition, EU has financed projects such as SCRREEN and Critical Raw Materials Recovery Project, who have given suggestions for improving the current situation.

higher recycling rates of CRMs. I compare the stated goals of WEEE legislation and its effects on recycling with the goals of Circular Economy. The goal is to find the areas of current legislation that inhibit progress towards Circular Economy goals. In addition, the purpose of this study is to investigate what key issues the legistator should pay attention to in order to facilitate Circular Economy more effectively, especially in the context of CRMs, in revisions to the legislation. Therefore the research question becomes twofold: The first question is to investigate what parts of current legislation impede CRM recycling and Circular Economy. The second question is to pinpoint the key issues that the legislation should target in order to improve CRM recycling, and offer suggestions on the direction of future legislation. As such, these research questions firmly place this thesis in the realm of regulatory theory. And while this subject may possibly appear overambitious for a Master's thesis, the previous legal scholarship on the subject is rather limited, which (hopefully) allows for a general overview to have value as self-standing work of jurisprudence.

1.3. Methods and research materials

The background material used in the thesis will for the most part constitute of previous studies that investigate the problem of CRM recycling from WEEE in the EU and in other parts of the world[21]. There have not been any comprehensive jurisprudential efforts to systematize the legal framework (and its problems) of CRMs and WEEE recycling.[22] Generally, the focus in previous studies on the matter has been on the economic and engineering bottlenecks of CRM recycling, while the legislative bottlenecks and potential remedies have been somewhat of a secondary interest.[23] From a research point of view, the

[21] United Nations Environment Programme (UNEP) studies on the matter, which take a global view, have been an invaluable resource in this work.

[22] Closest to critical legislative study comes SCRREEN, "Upgrading regulations and standards to enable recycling of CRM from WEEE", 2019 (SCRREEN, D8.2), which is a rather "thin" assessment and focuses more on industry standards than legislation (in addition, the paper is entirely written by engineers, without input from a legal scholar). An overview of the current status of EU WEEE legislation is provided in Vanessa Goodship, Ab Stevels, *Waste electrical and electronic equipment (WEEE) handbook* (Woodhead Publishing, 1st edition 2012, 2nd edition 2019). As it is intended as a basic handbook, it is neither a very critical nor particularly in-depth investigation.

[23] Such as the JRC publication Critical Raw Materials and the Circular Economy – Background report and Commission's Report on Critical Raw Materials and the Circular Economy.

relative esotericness of the subject, likely created by its interdisciplinarity and technicality, is somewhat of a challenge for the writer, as there is no previous framework set by environmental law scholars on this particular subject matter.[24] Therefore, this work is based mainly on analysis made by other scientific disciplines.

I have chosen to investigate and explain the technical problems of CRM recycling from WEEE at length for two reasons: The first one is that WEEE recycling is a complex process that effectively begins long before the waste enters a recycling facility. From this follows the second reason: an understanding of the entire process is necessary for formulating an expert opinion on the legislation.[25] An understanding of the life cycle of electronic products is necessary in order to pinpoint the areas where existing legislation fails to facilitate Circular Economy. The work also investigates the scientific (metallurgical) and economic aspects of WEEE recycling via existing literature[26], as effective legislation must work in tandem with those areas. The reason for this is that as noted by Faure, when drafting environmental policy, it is crucial that the policy maker is clearly aware of the practical effects of policy instruments and has *ex ante* empirical knowledge of their impact.[27] This is especially important in a subject as complex as CRM recycling from WEEE. As such, there is a degree of interdisciplinarity to the work, with an attempt to synthesize the practical and empirical with the legislative – an attempt in bridge-building.[28] Such mixture is necessary due to WEEE

[24] On the tendency of environmental law scholarship to "cluster" around certain subjects while disregarding others, see Elizabeth Fisher, Bettina Lange, Eloise Scotford, Cinnamon Carlarne: "Maturity and Methodology: Starting a Debate about Environmental Law Scholarship". Journal of Environmental Law 21:2, 2009, p. 230-231.

[25] Christian Hagelüken, "Recycling of (Critical) Metals", in Gus Gunn (ed), *Critical Metals Handbook* (John Wiley & Sons, 2014), p. 62.:"However, the required quantum leap can only be achieved by a holistic system approach and adequate policy support which takes the interdependencies of life-cycle steps, impact factors and measures into account"; and Henning Friege, "Review of material recovery from used electric and electronic equipment-alternative options for resource conservation". Waste Management & Research 30(9) Supplement 3–16, 2012, p.13.: "The field of electric and electronic devices is widely seen from the viewpoint of waste management. This is not sufficient. The problems coming up with the implementation of the directives are connected to scientific, economic and social phenomena- - The objectives of the Directive and the tools used for the implementation will fail as long as the dilemmas presented are not taken into consideration."

[26] For which there thankfully is an active research community, compared to jurisprudential investigations on the subject.

[27] Michael G. Faure, "Instruments for environmental governance: what works?". Paper presented at the Annual Colloquium of the Academy for Environmental Law of the IUCN, 2009, p. 25.

[28] See Malcolm K. Sparrow, *The Regulatory Craft : Controlling Risks, Solving Problems, and Managing Compliance* (Brookings Institution Press, 2000), p. xvii: "The topic of regulatory reform touches an alarming number of established academic disciplines- -To speak with any authority, perhaps academic commentators should also be required to know the particular sciences relevant to each regulatory field: biology, chemistry, and physics (for environmental protection)". Also, Fisher et al. 2009, p. 232.: "First, [environmental lawyers] need to develop contributory expertise- -[s]econd, scholars need to develop interactional expertise with other

recycling's state as a particularly "messy reality" that likely does not align itself well to strictly orthodox methodology.[29] This may sound more eccentric than it actually is; as mentioned by Määttä, the challenges of cross-disciplinary work in environmental law tend to be practical, not methodical.[30]

Policy research, as it is defined by Ann Majchrzak, is the overall approach used in this thesis.[31] It is defined by five characteristics: First of them is *multidimensionality*. It stems from the fact that the issues policy research investigates are complex and comprised of a large variety of interrelated factors. While a study is not expected to investigate all those factors, it should attempt to at least identify them and demonstrate their context to the issues that are chosen for a more focused study[32]. Second is the use of "empirico-inductive" approach, where the investigation begins with the study of the social problem and then seeks to empirically induce causal theories about it.[33] While following this form up to the letter is not possible in this thesis due to the length constraints, the work was very much devised that way. Third element is a focus on "malleable variables". In such a research the goal is to identify those variables of the problem that are open to "influence and intervention". As this thesis is first and foremost a jurisprudential investigation, its goal is to find those variables that can be influenced by regulation. Fourth characteristic is responsiveness to study users. One of the first steps of policy research is the identification of the users of the study. In this case, it is the regulator, and also all other actors (stakeholders) who have an interest in the bottlenecks of WEEE and CRM recycling. The final element is the explicit incorporation of

disciplines (both scientific and social scientific) so that their legal scholarship is based on a sound understanding of environmental problems."

[29] "Methodology problems are not likely to be effectively solved by assuming away the messy realities, merely to create the pretence of tractable 'scientific' research questions that fit available methodologies." Paul Martin and Donna Craig, "Accelerating the evolution of environmental law through continuous learning from applied experience". In *Implementing Environmental Law* (Cheltenham, UK: Edward Elgar Publishing, 2015), p. 34-35. See also David J. Herring, "Legal Scholarship, Humility, and the Scientific Method" (2006) for discussion about the relationship between legal scholarship and empirical sciences.

[30] Tapio Määttä, "Metodinen pluralismi oikeustieteessä – ympäristöoikeudellisen tutkimuksen suuntaukset ja menetelmät". In Tarmo Miettinen (ed), *Oikeustieteellinen opinnäyte – Artikkeleita oikeustieteellisten opinnäytteiden vaatimuksista, metodista ja arvostelusta* (Edilex 2015), p. 54.

[31] Ann Majchrzak, *Methods for policy research* (SAGE Publications, Inc., Thousand Oaks, California, 1984), Chapter 1: "The Nature of Policy Research", section "Characteristics of policy research studies".

[32] In the context of this study, the problem of illegal WEEE exports is such an issue.

[33] Which, as Majchrzak notes, differs significantly from "traditional" scientific approach where the usual structure of a study is to test a pre-constructed hypothesis. However, it likely is far less unconventional in legal research, where, due to the nature of the object of study (law), starting with a preconceived hypothesis would often be unwieldy.

values into the study. The social problem is investigated from a frame of preconceived value and it forms the lens through which the research investigates its object of study.[34] In this thesis, that value is Circular Economy.

The method that will be used is regulatory theory. The focus of the work is evaluative investigation of current legislation with a problem-centred approach and *de lege ferenda*. Descriptive and interpretative study of current legislation is done only in support of those goals.[35] The current legislation will not be examined de lege lata beyond the parts that are deemed counterproductive to CE (this excludes issues such as BAT requirements from this thesis). The goal of the work is to identify the critical issues that must be targeted in order to improve the legislation in solving the problems of CRM recycling from WEEE.[36]

I limit the thesis to investigating only the WEEE legislation on EU level because it is completely infeasible to cover the global scope of the matter in the space of a Master's Thesis. Meanwhile, focusing on only one state (e.g. Finland) would be counterproductive due to the fact that effective CRM recycling requires wider material flows than is available from one state.[37] As such, EU's size as a legislative and economic entity is optimal for the purposes of this thesis. In addition, the focus is only on CRMs and their recycling (and not on other materials), because CRM recycling in WEEE on EU level is a subject that has not gained a lot of attention in legal studies before, even though waste and recycling is otherwise a (relatively) "popular" subject of study. In addition, this thesis will not attempt to solve the issues related to ineffective enforcement of WEEE legislation, even though it is a significant bottleneck (not just for CRM recycling but for WEEE in general),[38] as it would require a

[34] *Ibid.*
[35] In environmental law, evaluative approaches have been less common than "traditional" descriptive and explanatory approaches. See for example Martin and Craig 2015, p. 32.
[36] As said by Paul Martin and Donna Craig: "It is clear that our scholarship will have to expand further, so that we can marry to good doctrinal approaches a new set of methods to provide comprehensive and sophisticated governance solutions to a world increasingly in need of them- -[t]his can only be done if we can draw upon the knowledge that exists in economics, social sciences and the biophysical natural sciences- -but without submerging- - **lawyers learned scepticism about simple solutions to complex problems**." (Emphasis mine) In Martin, Paul, Li. Zhiping, Qin Tianbao, Anel Du Plessis, Yves Le Bouthillier, Angela Williams, *Environmental Governance and Sustainability* (Cheltenham, UK: Edward Elgar Publishing 2012), p. xxxi.
[37] This is discussed further in Section 5.6.
[38] For example, see Countering WEEE Illegal Trade (CWIT) Summary Report, "Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap" (2015), and EucoLight study on non-compliance with national WEEE requirements, <https://www.eucolight.org/single-post/2019/11/08/EucoLight-conference-reveals-disturbing-EU-wide-scale-of-WEEE-non-compliance-through-online-marketplaces-and-new-ways-to-tackle-the-problem> (Accessed 29.3.2020).

completely separate study with different methodology and approach. Finally, the thesis shall only cover issues related to improving recycling rate of electronics and ignores increasing re-use, even though the latter would also increase resource efficiency (at least temporarily).[39] This is due to the fact that electronic technology develops constantly and even with extensive re-use, products and components will almost inevitably become, sooner or later, technologically outdated and in need of replacement, necessitating material recovery from them.

As mentioned, the intended audience (or the role reader should imagine herself as) is the regulator, and Circular Economy forms the normative premise of the work: is the evaluative lens through which the effectiveness of current legislation is judged, and it is the goal of all *de lege ferenda* suggestions presented in the thesis. The materials that will be used are EU legislation, Commission papers, different project outputs on the subject of WEEE and CRMs, and engineering papers covering WEEE recycling. In addition, the thesis is created via co-creation method that involves interdisciplinary discussions and sharing.[40] Outotec is a partner in the project and has provided information and stimulus for the thesis via their representative who has been a part of both co-creative and private discussions.

[39] And it is placed higher in the Waste Hierarchy (which may be to a degree one of the problems of current legislation, see section 4.4).
[40] For an overview of co-creation method, see Clark A. Miller, Carina Wyborn, "Co-production in global sustainability: Histories and theories". Environmental Science & Policy, 2018.

2. The Framework of WEEE Recycling and Circular Economy

2.1. What is the WEEE Directive?

Directive 2012/19/EU (WEEE Directive) legislates the treatment, handling and disposal of discarded electronic products and equipment (both consumer and professional) on EU level. Its goal is to prevent pollution and health hazards caused by incorrectly disposed electronics and to reduce the waste of precious materials via the promotion of re-use and recycling. The creation of a directive aimed specifically to waste electrical and electronic equipment (WEEE) was deemed necessary for several reasons. One of them is that WEEE is one of the fastest growing waste streams in the EU and in the world.[41] Another reason is that WEEE is potentially hazardous waste stream if handled improperly. Though WEEE is mainly constituted of base metals, including iron, copper and aluminium, it also contains hazardous substances, such as brominated flame retardants, lead, beryllium, and arsenic[42]. The third reason is that WEEE also contains important materials that should be recovered whenever possible. One category of such metals is the aforementioned base metals, but WEEE is also a source of precious metals, e.g. gold, silver and palladium. In addition, WEEE contains special metals and materials classified as Critical Raw Materials (CRM) by the EU, which are the main focus of this study. These include indium, gallium, cobalt, silicon and REEs.[43]

[41] European Commission, Waste Electrical & Electronic Equipment (WEEE) <https://ec.europa.eu/environment/waste/weee/index_en.htm> (Accessed 13.2.2020).

[42] Many of these materials (“legacy substances”) are in the process of being phased out due to the introduction of the RoHS Directive. Still, a significant amount of hazardous substances will remain in WEEE, as some substances do not have feasible, effective and safe substitutes. Examples include mercury in lamps and LCD panels. Further, Commission staff working paper, Impact assessment on the proposed directive on waste electrical and electronic equipment [2008] COM(2008) 810 final, p. 30. and Communication from the Commission on the implementation of the circular economy package: options to address the interface between chemical, product and waste legislation [2018], COM/2018/032 final, p. 4. However, it can be noted that technology can change quickly in EEE products, as the abovementioned working paper from 2008 mentions lead in cathode ray tubes as a significant issue – yet today CRT screens are effectively dead technology, superseded by advances in LCD displays.

[43] UNEP (2013), Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M. A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C., Appendix B: Details on Metals found in WEEE, and European Commission 2015. Study on WEEE recovery targets.

In the case of all these materials, recovery will lead to significant energy, CO_2 and environmental savings.[44]

The purpose of the WEEE Directive is to ”to contribute to sustainable production and consumption by, as a first priority, the prevention of WEEE and, in addition, “*by the re-use, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste and to contribute to the efficient use of resources and the retrieval of valuable secondary raw materials*.”[45] In this it is designed to “supplement”[46] the overall waste legislation and policy of the EU, mainly the Directive 2008/98/EC (Waste Framework Directive). The WEEE Directive is based on the Waste Framework Directive in all its key areas, such as definition of waste[47] and other significant definitions such as “recycling”[48]. It also follows the principles of the waste hierarchy set by Waste Framework Directive[49] in its commitment to promote prevention of waste first, then to aim for re-use and recycling, and to settle for energy generation and finally landfill as a last resort. In addition, it follows the general principles of the EU environmental and waste legislation, such as precautionary principle, preventive principle and polluter pays-principle.[50]

The WEEE directive is mainly built on top of the existing waste legislation of the EU, as can be seen by its stated “supplementary” role to the Waste Framework Directive. Its main features are the collection and recycling targets that it sets for the producers of electronic products. There responsibilities are created via the concept of Extended Producer Responsibility (EPR).[51] EPR, in a wider context, means that the producers accept significant

[44] Cite note 10 and UNEP 2013, Section 2.4, “Benefits from increased recycling” and 2.5, “The contribution to sustainable development”.
[45] WEEE Directive (Directive 2012/19/EU), Preamble 6.
[46] Directive 2012/19/EU, Preamble 4: “This Directive supplements the general waste management legislation of the Union, such as Directive 2008/98/EC-“. There are other supplementary directives set for other specific waste streams, such as packaging waste. A comprehensive list of these can be found at <https://ec.europa.eu/environment/waste/legislation/c.htm> (Accessed 17.2.2020).
[47] Directive 2012/19/EU Article 3.1.e: ”‘WEEE’ means electrical or electronic equipment which is waste within the meaning of Article 3(1) of Directive 2008/98/EC”.
[48] Directive 2012/19/EU Article 3.2: ”In addition, the definitions of ‘hazardous waste’, ‘collection’, ‘separate collection’, ‘prevention’, ‘re-use’, ‘treatment’, ‘recovery’, ‘preparing for re-use’, ‘recycling’ and ‘disposal’ laid down in Article 3 of Directive 2008/98/EC shall apply.
[49] Waste Framework Directive (Directive 2008/98/EC), Article 4.
[50] Directive 2012/19/EU, Preamble 2.
[51] Directive 2012/19/EU, Article 7.

responsibility for the waste management of discarded consumer products[52], Currently, the collection rate is set to be 65 % of the average weight of EEE placed on the market in the three preceding years in a Member State, or alternatively 85 % of WEEE generated on the territory of Member State.[53] The re-use and recovery targets are set in Annex V of the directive, and they vary slightly between specific sub-streams of WEEE.[54] The responsibility to implement EPR is on the Member States, which they must enforce on their territory.

WEEE Directive also sets requirements for separate collection of WEEE. Separate collection means that WEEE should not be mixed with unsorted municipal waste, but collected separately.[55] This is required in order to ensure that the WEEE would be treated properly in specialized facilities, first in order to increase recycling efficiency[56]; second, due to their material content, discarded electronic products can be hazardous to environment if treated and/or disposed improperly without proper precautions. To supplement this, the Directive also has requirements for “proper treatment”[57] of WEEE and a prohibition to dispose WEEE when it has not undergone such treatment.[58] “Proper treatment” at a minimum level requires the removal of all fluids from the disposed product. Further treatment requirements are made for specific products and components in the Annex VII (Selective treatment). These include, inter alia, the removal of batteries, specific circuit boards[59], toner cartridges, and potentially hazardous substances, such as mercury-containing components, asbestos, brominated flame

[52] OECD, *Extended Producer Responsibility: A Guidance Manual for Governments* (OECD Publishing, Paris, 2001). EPR is discussed in further detail in section 5.2.
[53] Directive 2012/19/EU, Article 7. Previously, the collection rate was set as 4 kilograms on average per inhabitant per year of WEEE from private households, which garnered criticism, as it incentivized the collection of heavy waste products such as electric stoves, ignoring light but metal-rich products such as mobile phones. Christian Hagelüken, “The challenge of open cycles – Barriers to a closed loop economy demonstrated for consumer electronics and cars”. Conference paper, 2007, p. 9.
[54] Recovery targets vary from 85 % to 75 %, depending on the category. The categories are set in Annex I and they are: 1. Large household appliances; 2. Small household appliances; 3. IT and telecommunications equipment; 4. Consumer equipment and photovoltaic panels; 5. Lighting equipment; 6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools); 7. Toys, leisure and sports equipment; 8. Medical devices (with the exception of all implanted and infected products); 9. Monitoring and control instruments; 10. Automatic dispensers.
[55] Directive 2012/19/EU, Article 5.
[56] Due to how materially different WEEE is from average municipal waste, without separate collection any sort of efficient recovery would be nearly impossible (with current technology).
[57] Directive 2012/19/EU, Article 8.
[58] Directive 2012/19/EU, Article 6.1.
[59] “[P]rinted circuit boards of mobile phones generally, and of other devices if the surface of the printed circuit board is greater than 10 square centimetres”.

retardants, polychlorinated biphenyls (PCB) and different classes of fluorocarbons (CFCs, HCFCs, HFCs).

Lastly, the Directive sets requirements (in Article 10 and Annex VI) for shipments of WEEE, and particularly for distinguishing between (legitimate) shipments of EEE and illegal shipments of WEEE. The goal is to limit the shipments of WEEE outside of EU's borders, especially in accordance with Basel Convention on the control of transboundary movements of hazardous wastes and their disposal. As mentioned previously, WEEE is potentially hazardous and especially so if treated and landfilled without proper treatment and infrastructure[60], and aforementioned legislation is in place to prevent WEEE from being shipped to places without adequate treatment facilities. In fact, illegal shipments of WEEE are a major problem: according to Countering WEEE Illegal Trade (CWIT) study, 1.3 million tons of WEEE departed the EU via undocumented exports in 2012 (in comparison, 3.3 million tons was officially reported as collected by the legitimate collection and recycling systems).[61] Of note is also that according to the study, 3.15 million tons of WEEE was recycled under conditions that are not compliant with WEEE and Waste Framework directives, showcasing severe problems with enforcement of the directive.

2.2. Circular economy and Green Deal

EU is committed to Circular economy and sustainable development, especially so since the introduction of the "Green Deal" in December 2019, where recycling is considered one of the key sectors in the project that aims to achieve a climate-neutral "green economy".[62] Circular economy forms the cornerstone of the Green Deal's new industrial policy, where the goal is "sustainable products" in which material use is reduced and when a product is

[60] The town of Guiyu in southern China is a famous and extreme example. See for example Anna Leung; Nurdan Duzgoren-Aydin; Kwai Cheung; Ming Wong, "Heavy Metals Concentrations of Surface Dust from e-Waste Recycling and Its Human Health Implications in Southeast China". Environmental science & technology. 42. 2674-80, 2008.
[61] CWIT 2015, p.6. The potential where the waste is shipped include Guiyu of the cite note above.
[62] European Commission, What is the European Green Deal? 2019.

disposed of, its materials are reused and recycled as much as possible.[63] Conceptually, Circular Economy is an antonym for *linear economy*[64], which is characterized by so-called "take-make-consume and dispose"-pattern where the flow of materials is linear and discarded materials effectively disappear from the economy via landfilling and other forms of disposal where materials are not recovered. In addition, a circular economy is characterized by low consumption of energy, low emission of pollutants and high efficiency.[65] However, at times circular economy has proven to be hard to define with exactness, and grasping its implications has appeared to be difficult at times in academic

discourse.[66] The origin of the concept is in the work of business practicioners, which may be the reason why the term is somewhat vague in its content[67] (though as legal scholars are aware, some concepts are better left open for interpretation).

However, any definition of Circular Economy must combine two aspects: environmental and economical. Korhonen et al. define Circular Economy environmental goals as reducing the use of virgin material and energy inputs in production and consumption stage of the products, and waste & emissions outputs in all stages of the product. Economic targets are to reduce the costs of raw materials, energy, waste management and emissions control, improving public image and facilitating innovation and creation of new markets.[68] In addition, for the purposes of this thesis, the overall goal of the Circular Economy is considered to be to *decouple economic growth from the use of virgin raw materials*. In this context, recycling's

[63] European Commission, Sustainable industry factsheet. 2019.
[64] Murray A, Skene K, Haynes K., "The Circular Economy: An interdisciplinary exploration of the concept and application in a global context". Journal of Business Ethics 2015, p.7. Also of interest is the term used by K.E. Boulding to describe linear resource use: *cowboy economy*. K.E Boulding, "The economics of coming spaceship earth", in H. Jarret (Ed.), *Environmental quality in a growing economy* (MD University press, 1966).
[65] UNEP (2006), *Circular Economy: An alternative for economic development* (Paris: UNEP DTIE), p. 1.
[66] Julian Kirchherr; Denise Reike; Marko Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions". Resources, Conservation and Recycling Volume 127, December 2017: "Our analysis of 114 definitions provides the first quantitative evidence that and how CE means many different things to different people, as also indicated by a comment of a reviewer of this paper who noted, upon skimming through the definitions analysed for this work, that "*some of the authors […] seem to have no idea about what [CE] is about*" (emphasis mine). On different conceptualizations of Circular Economy, see Ellen MacArthur Foundation, "Circular Economy: Schools of Thought" <https://www.ellenmacarthurfoundation.org/circular-economy/concept/schools-of-thought> (Accessed 22.1.2020).
[67] Korhonen, Jouni & Honkasalo, Antero & Seppälä, Jyri, "Circular Economy: The Concept and its Limitations". Ecological Economics 143, 2018, p. 37–46.
[68] Korhonen et al. 2018, p. 41.

primary goal is to increase the utilization of materials that are already present within the economy and "close the loop" of material flows.

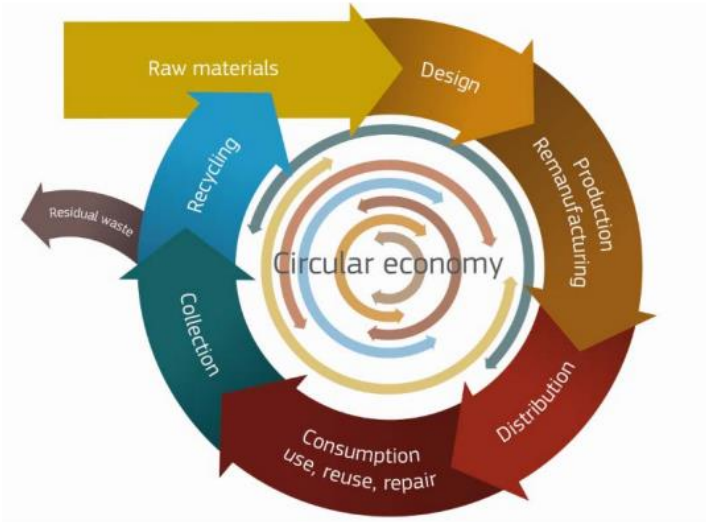

Figure 2: Visualization of circular economy.[69]

It has been stated that the move to a circular economy could become "the second major European political economy project after establishing the internal market",[70] and it also is planned to be "the number one priority" in the European Green Deal.[71] In the EU Environment Action Programme to 2020 (7th EAP), Member States and the European Parliament decided to establish indicators and set targets for resource efficiency. The European Resource Efficiency Platform recommends that the EU should aim for at least a 30 % increase in resource efficiency. Resource efficiency is measured by GDP on Raw Material Consumption, which is an aggregate indicator measuring (in tonnes) all the resources used in the economy, while taking to account resource use embedded in imports.[72]

[69] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Towards a circular economy: A zero waste programme for Europe [2014], COM/2014/0398 final, p. 5.
[70] Ellen MacArthur Foundation, *Growth within: A circular economy vision for a competitive* (2015), p. 29.
[71] Frédéric Simon, "Circular economy erected as 'number one priority' of European Green Deal" <https://www.euractiv.com/section/circular-economy/news/circular-economy-is-number-one-priority-of-european-green-deal/> *EURACTIV.com* (13 Nov 2019).
[72] Questions and answers on the Commission Communication "Towards a Circular Economy" and the Waste Targets Review, 2014. <https://ec.europa.eu/commission/presscorner/detail/en/MEMO_14_450> (Accessed 15.1.2020).

If that goal were reached, it could boost GDP by nearly 1 % while creating over two million jobs, compared to scenario without such resource efficiency improvement. This would have the dual impact of improving resource supply security within the EU while simultaneously reducing harmful impacts on the environment.[73]

Therefore there is significant pressure to transition towards circular economy. As noted in the Commission's communication on the European Green Deal, from 1970 to 2017, the annual global extraction of materials tripled and the growth has continued to this day,[74] which the Commission describes "a major global risk".[75] Of global greenhouse gas emissions, about 50 % of them are created by resource extraction and material processing, and for biodiversity loss and water stress this effect is 90 %. In EU's highly developed economy, the effect of industry's greenhouse gas emissions are far smaller, 20 %, though it must be noted that the EU also imports products which affect its actual per capita carbon footprint.[76] Of the materials used in European manufacturing, only 12 % on average come from recycling[77], and as has been noted, in CRMs even less. In addition to environmental benefits, increasing the use of recycled materials in fabricated metal products is estimated to improve their resource efficiency by over 20 %.[78] It also appears that linear economy model is reaching its inherent limits, exposing the industry and society to increased resource prices and supply risks, as its efficiency gains are slowing down and supply chains are becoming increasingly elaborate and fragile.[79]

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[73] Questions and Answers on the Commission Communication 'Towards a Circular Economy' and the Waste Targets Review,' [2014], p. 2.
[74] COM(2019) 640 final, p. 7, International Resource Panel (IRP), *Global Resources Outlook 2019: Natural Resources for the Future We Want: A Report of the International Resource Panel* (United Nations Environment Programme, Nairobi, 2019).
[75] COM(2019) 640 final, p 7.
[76] Eurostat, Greenhouse gas emission statistics - carbon footprints, <https://ec.europa.eu/eurostat/statistics-explained/pdfscache/10389.pdf> (Accessed 28.2.2020).
[77] Eurostat, Circular material use rate - % of total material use <https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=cei_srm030&plugin=1> (Accessed 28.2.2020). The circular material use (CMU) rate measures the share of material recovered and fed back into the economy — thus saving extraction of primary raw materials — in overall material use.
[78] European Commission, "The opportunities to business of improving resource efficiency: Final Report" (AMEC Environment & Infrastructure and Bio Intelligence Service, 2013). <https://ec.europa.eu/environment/enveco/resource_efficiency/pdf/report_opportunities.pdf> (Accessed 12.1.2020).
[79] World Economic Forum, *Towards the circular economy: Accelerating the scale-up across global supply chains* (2014), p. 13-14, 21-22. Also of note is that during the writing of this thesis, the COVID-19 -crisis has raised the issue of fragileness of modern global supply chains into public discussion.

In the revised Circular Economy Action Plan of 2020, one of the planned projects for a new industrial strategy of the EU is a circular electronics initiative, which will be a part of the overall goal to reduce the carbon and material footprint of European industry and "embedding circularity across the economy". Developing industrial innovation is one of the key parts of the new industrial strategy, and one of the targets is to incentivize different industry sectors to "define their own roadmaps for climate neutrality". [80] The EU has identified CRMs as one of the key areas of Circular Economy. It recognizes that WEEE is a potential source of CRMs, and that the current very low recycling rate of these materials means that significant economic opportunities are lost. The EU has stated that increasing the recovery of critical raw materials is one of the challenges that must be solved on the road towards a circular economy.[81]

[80] Communication from the Commission on A New Industrial Strategy for Europe [2020], COM/2020/102 final.
[81] COM/2015/0614 final, p. 15-16.

3. Critical Raw Materials, WEEE and Circular Economy

3.1. What are Critical Raw Materials?

Critical Raw Materials (CRMs) are materials and substances that the EU considers vital for its economy. To be considered critical, a material must have two attributes: high economic importance to the EU and a high risk associated with its supply.

So far, the EU has released three Critical Raw Material lists, the first in 2011 (containing 14 materials)[82], a revised version in 2014 (20 materials)[83], and the most current one in 2017 (27 materials)[84]. CRM assessments are a part of EU:s Raw Material Initiative, which was launched in 2008.[85] The initiative is based on three pillars: Fair and sustainable supply of raw materials from global markets; sustainable supply of raw materials within the EU; and resource efficiency and supply of secondary raw materials through recycling.

CRMs are essential for the production of a broad range of goods and services, especially in the realm of advanced technology.[86] For example, tungsten is used widely in industrial applications, electronics, the automotive and aerospace industries and medical technology. REEs are extremely important in the development of "green technology", which is a key area of technology for lowering emissions and increasing the material and energy efficiency of certain key products.[87] The development and production of low-carbon technologies is

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[82] COM/2011/0025 final.
[83] COM/2014/0297 final.
[84] COM/2017/0490 final.
[85] Communication from the Commission on The raw materials initiative: meeting our critical needs for growth and jobs in Europe [2008], COM/2008/0699 final.
[86] British Geological Survey; Bureau de Recherches Géologiques et Minières; Deloitte Sustainability; Directorate-General for Internal Market; Industry, Entrepreneurship and SMEs (European Commission); TNO, *Study on the review of the list of critical raw materials – Criticality assessments* (EU Publications 2017), p. 10.
[87] For a review, Gutfleisch, O., Willard, M. A., Brück, E., Chen, C. H., Sankar, S. G., & Liu, J. P., "Magnetic materials and devices for the 21st century: stronger, lighter, and more energy efficient". Advanced Materials, Vol. 23, No. 7, 2011, p. 821-842; John Seaman, *Rare Earths and China: A Review of Changing Criticality in the New Economy* (Notes de l'Ifri, 2019), p. 20; and I.R. Harris; G.W. Jewell, "Rare-earth magnets: properties, processing and applications", in John A. Kilner; Stephen J. Skinner; Stuart J.C. Irvine; Peter P. Edwards (eds.) *Woodhead Publishing Series in Energy, Functional Materials for Sustainable Energy Applications* (Woodhead Publishing, 2012), p. 600-639. For example, dysprosium (and other REEs) are used in high power magnets, which are a critical component in many high-tech applications, such as wind turbines. High power magnets allow for efficient energy transmission, which means they are a critical material for developing renewable energy technology. Rare earths can also greatly increase the energy efficiency of air conditioning and refrigeration applications via the use of improved magnetic materials, which will directly contribute to lower

expected to drive the demand of certain materials up by a factor of 10-20 by 2030.[88] In addition, nearly all advanced electronic technology uses at least some CRMs, as they're necessary for their important features or level of performance.[89] The "criticality" of different materials is measured on set criteria:[90]

- Economic importance, measured via assessing the importance of end-use applications and the value added to corresponding EU manufacturing sectors;
- Supply risk, calculated via the concentration of primary supply from raw materials producing countries, considering their governance performance and trade aspects. Supply risk is measured at the 'bottleneck' stage of the material, which means that its importance is measured at its most crucial stage in the supply chain.

These measurements are a combination of different factors that were considered during the creation of CRM lists. For assessing economic importance, the substitutability (substitution index) of the materials was one of the considerations – could some other material be used in its place and how technologically and economically viable such replacement would be?[91] Most CRMs are characterized by extremely low substitution rates, meaning that they cannot realistically be replaced by the use of a less critical material.[92]

CO_2 emissions as air conditioning and refrigeration are the biggest energy consumers in the domestic market. Electric car batteries also require rare earths to achieve high efficiency. See also JRC 2017, p. 66. Finally, for an overview on the importance of CRMs: European Commission, Critical Raw Materials <https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en> (Accessed 18.2.2020).

[88] 10 for REEs (due to need for high-power magnets), 20 for lithium (due to need for advanced batteries). Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, *EU Raw Materials Scoreboard 2018* (EU Publications 2018), p.15. In addition, see SCRREEN, "Report on major trends affecting future demand for critical raw materials", 2018, and SCRREEN, "Report on the Future Use of Critical Raw Materials", 2018. The use of indium (LCD screens), cobalt (batteries) and REEs (neodymium and dysprosium for magnets) is expected to rise significantly over the next decades.

[89] For example, in addition to the examples mentioned in cite notes above, touchscreens and modern digital displays require the use of, inter alia, Indium, Cerium, Yttrium and Terbium for their functionality, and circuit boards employ Platinum group metals.

[90] European Commission, Critical Raw Materials <https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en>(Accessed 18.2.2020).

[91] British Geological Survey et al. 2017, p. 29-30.

[92] COM(2017) 490 final, p. 4-7.

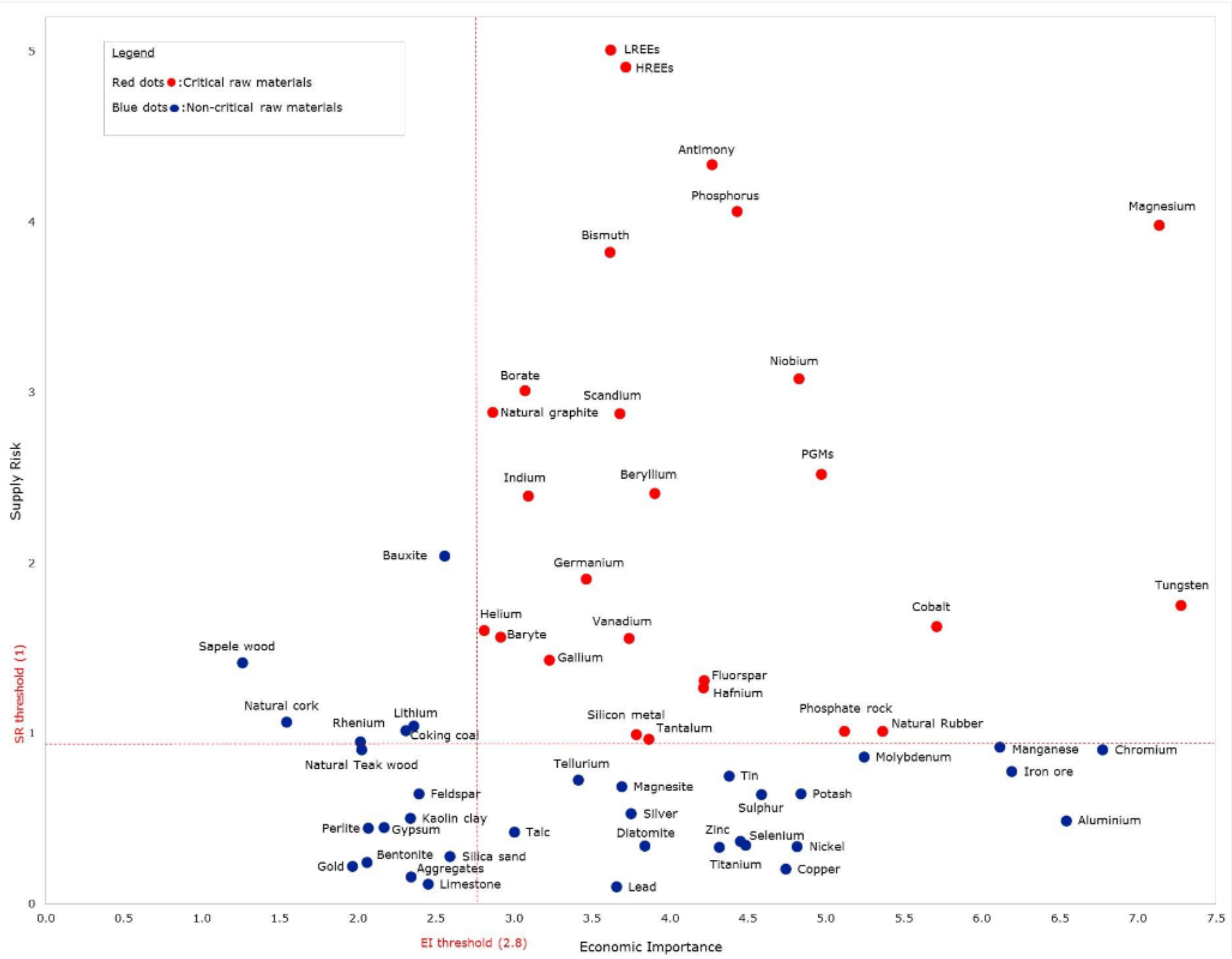

Figure 3: Critical raw materials chart from 2017 CRM assessment.

As can be seen, highest supply risks are considered to involve light and heavy REEs (LREEs and HREEs) [93]. It should be noted that REEs are a collection of 17 different elements, even though they are counted as one CRM in the list of CRMs[94]. While there is some variance between different elements, generally for all of them China is the main supplier – 95 % of

[93] There are 17 rare earth elements: cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lanthanum (La), lutetium (Lu), neodymium (Nd), praseodymium (Pr), promethium (Pm), samarium (Sm), scandium (Sc), terbium (Tb), thulium (Tm), ytterbium (Yb), and yttrium (Y). Despite their name, rare earths are not "rare" in earth's crust. However, unlike many metals, they rarely are concentrated in exploitable ore deposits but instead distributed evenly in earth's crust in low concentrations, hence their name.

[94] Which may be problematic, as different REEs are used for different applications and have different properties. See for example V. Balaram, "Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact". Geoscience Frontiers, Volume 10, Issue 4, 2019, p. 1285-1303.

their global production is situated there, and of EU's use, 40 % come from China, 34 % from USA and 25 % from Russia, and their import rate is 100 %.[95]

Criticality rates are not binary, as can be seen from Figure 3. Instead, criticality is a sliding scale with multi-dimensional aspects: First one of them is that criticality is always to a degree subjective – what is irreplaceable for some industries is non-necessary for some.[96] To this is related that criticality of materials is not static, but instead affected by the directions that technological advance takes in different fields. Crucial technologies of tomorrow may require different elements than current ones, and critical materials of today may be substituted by better available ones in the future (there is significant incentive to find such substitutions). Another factor that can change the criticality of a material is geopolitical change: a material can develop a supply risk if the area where it is produced becomes unstable or geopolitical tensions arise. For these reasons, assessments of criticality should be considered to only reflect the current state of affairs.

3.2. Critical Raw Materials and WEEE

WEEE is a significant source of CRMs.[97] Examples of CRMs in WEEE include: beryllium, cobalt, germanium, indium, natural graphite, platinum group metals, REEs, silicon metal and tungsten.[98] The concentrations of CRMs tend to be relatively high in WEEE relative to ores found in mines[99], making WEEE a potential resource – a so-called "urban mine" of materials.[100] However, as mentioned already, the recycling rate and recycling input rate of

[95] COM/2017/0490 final, p. 7.
[96] T.E. Graedel; Gus Gunn; Luis Tercero Espinozain, "Metal resources, use and criticality". In Gus Gunn (ed.) *Critical Metals Handbook* (John Wiley & Sons, 2014), p. 10-14. In addition, the growth of the CRM list of EU from 14 materials to 27 underlines the inherent subjectivity.
[97] Hagelüken; Meskers 2012, p. 49-52.
[98] JRC 2017, p. 30.
[99] Though there is a lot of variance in product and component compositions, which is a significant quality of WEEE in the context of recycling and presents unique challenges. This will be discussed in more detail in sections 4 and 5.
[100] Jaco Huisman, Pascal Leroy, François Tertre, Maria Ljunggren Söderman, Perrine Chancerel, Daniel Cassard, Amund N. Løvik, Patrick Wäger, Duncan Kushnir, Vera Susanne Rotter, Paul Mählitz, Lucía Herreras, Johanna Emmerich, Anders Hallberg, Hina Habib, Michelle Wagner, Sarah Downes. "Prospecting

these materials is very low and in their case Circular Economy is not realized in practice.[101] This is problematic for several reasons, which shall be discussed in the following sections.

3.2.1. Environmental impact of CRM mining

From the perspective of reducing environmental impacts, reducing the use of virgin raw materials is extremely important: According to IRP's 2019 study, globally 90 % of biodiversity loss and water stress are caused by resource extraction and processing.[102] Environmental pollution and health hazards are especially prevalent with the mining of CRMs, and in the context of CRMs, REEs are a particular offender. The mining of heavy metals, such as mercury, arsenic, lead, zinc and cadmium, creates mining waste that is prone to leakage of hazardous substances to the environment, and CRMs are often mined as a co-product of these materials.[103] Minerals that contain REEs also contain low levels of radioactive isotopes that can become concentrated in mine tailings. The radionuclides are released as dust during mining or from exposed waste rock stockpiles and are difficult to prevent escaping into nature, as the radiation can leak into the ground or into water streams if the mining waste is not stored properly.[104] When the radionuclides are released into an ecosystem, they accumulate in plants and then ascend the food chain.[105] In addition, the tailings can contain fluorides, sulphides, acids and heavy metals.[106] The tailings are often

Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report" (Brussels, 2017). <http://www.prosumproject.eu/sites/default/files/DIGITAL_Final_Report.pdf> (Accessed 5.4.2020).

[101] For additional overviews, see, JRC 2017, p. 41-43. and LIFE 2014 CRMRecovery[sic], "Critical Raw Material Closed Loop Recovery, Layman's Report", p. 4.

[102] IRP, *Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel* (United Nations Environment Programme. Nairobi, Kenya 2019).

[103] Jurate Miliute-Plepiene; Lena Youhanan, *E-waste and Raw Materials: From Environmental Issues to Business Models* (IVL Swedish Environmental Research Institute, 2019), p. 17.

[104] MIT, "Environmental Risks of Mining – How they arise and how their effects can be mitigated" (MIT, 2012) <http://web.mit.edu/12.000/www/m2016/finalwebsite/problems/mining.html> (Accessed 17.2.2020). Nawshad Haque; Anthony Hughes; Seng Lim; Chris Vernon, "Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact". Resources 2014, 3, p. 614-635.

[105] Paul, J., & Campbell, G., "Investigating rare earth element mine development in epa region 8 and potential environmental impacts (908R11003)" (U.S. Environmental Protection Agency, 2011).

[106] Schüler D., M. Buchert, R. Liu, S. Dittrich, C. Merz, 2011. "Study on Rare Earths and Their Recycling, Final Report for The Greens/EFA Group in the European Parliament, Darmstadt, January, 2011". Öko-Institut e.V, 2011, p. 44.

stored in pools and dams that are at risk of overtopping due to storm water, poor construction or seismic events.[107]

The CO_2 impact of primary production of CRMs that are used in electronic products ("technology metals") is also significantly higher than that of base metals. This is due to several reasons. First, their concentrations in nature tend to be lower than that of base metals, so their mining requires higher use of labor and resources. Second, their separation demands more energy, because the metals are (mostly) not noble. Recycling these metals efficiently can result in significant CO_2 savings (in addition to the reduced environmental impacts from mining) due to the fact that the metals are present in WEEE in much higher concentrations than in nature.[108]

Environmental issues are exacerbated by the fact that most of CRM mining (especially of materials that are used in electronic products) is situated in countries with poor infrastructure and lower environmental standards than those of EU, namely China and African nations – as mentioned previously, Europe produces almost zero REEs and platinum group materials, and the import rate for these metals is effectively 100%.[109] China has closed some of its REE mines because their environmental impacts were extremely heavy.[110] Even though these environmental issues do not impact the EU directly, it does mean that the Union effectively externalizes the environmental impacts and risks of CRM mining. At the same time, the EU is one of the largest producers and consumers of automotive, electrical and electronic goods that contain platinum group metals and rare earths.[111] And was noted previously, the demand

[107] Schüler et al 2011, p. 61.
[108] Christian Hagelüken; Christina E.M. Meskers, "Recycling of Technology Metals – A Holistic System Approach", in Hieronymi K, Kahhat R, Williams E,. London (eds.), *E-Waste Management : From Waste to Resource* (Routledge; 2012), p. 55. Expected CO_2 savings for recycling vary between 20-90 %, with some variances across different metals. See also UNEP 2013, p. 84-85.
[109] Communication from the Commission on the 2017 list of Critical Raw Materials for the EU [2017], COM(2017) 490 final.
[110] For examples, G. Pitron, "La guerre des métaux rares: La face cache de la transition énergétique et numérique", Paris: Les Liens qui Libèrent, 2018; D. S. Abraham, "The Elements of Power: Gadgets, Guns, and the Struggle for a Sustainable Future in the Rare Metal Age", p. 176; H. Liu, "Rare Earths: Shades of Grey – Can China Continue to Fuel Our Global Clean & Smart Future?", China Water Risk, 2016; Michael Standaert, "China Wrestles with the Toxic Aftermath of Rare Earth Mining". Yale Environment 360, Yale School of Forestry & Environmental Studies 2019, <https://e360.yale.edu/features/china-wrestles-with-the-toxic-aftermath-of-rare-earth-mining> (Accessed 20.2.2020) Also, the Chinese Society of Rare Earths estimates that producing one ton of REEs also produces 75,000 liters of acidic wastewater and one ton of radioactive residue.
[111] European Rare Earths Competency Network (ERECON), "Strengthening of the European Rare Earths Supply Chain - Challenges and policy options", 2015, p. 48.

for different CRMs is expected to rise by factors of 5–20[112] – however, according to the principles of Circular economy, virgin raw material demand should be decoupled from economic growth.[113]

Of note are also the so-called conflict minerals, which are materials that are mined in resource-rich, conflict-affected areas. Buyers of such minerals face the risk of financing armed groups and other illegal entities. The EU has set Regulation 2017/821 laying down supply chain due diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and gold originating from conflict-affected and high-risk areas. Reducing export dependency on these metals via recycling would help in reaching the goals of the regulation.

3.2.2. CRM supply risks and recycling

As mentioned, the EU produces very few CRMs on its soil and is wholly reliant on imports. This exposes the Union to supply risks. This is especially the case with REEs, as majority of the world's production is located in China,[114] with which there is an existing history of geopolitical tensions. China already has previously introduced export restrictions for REEs, implementing them during 2010.[115] In addition, even though there is a developing mining industry on mining of REEs outside of China, they mainly focus on LREEs, while China still effectively is the sole producer of HREEs[116], which are considered to be nearly insubstitutable.[117] For tungsten, even though 84 % of global production is held by China, it does not supply the EU at all, and the highest share of EU supply is provided by Russia (50%), with other sources being Portugal (17%), Spain (15%) and Austria (8%) – therefore the import reliance rate for tungsten is currently "only" 44%. In the case of PGMs, their

[112] EU Raw Materials Scoreboard 2018 and SCRREEN, "Report on the Future Use of Critical Raw Materials", 2018.
[113] For example see Bringezu, Stefan, "Key Elements for Economy-wide Sustainable Resource Management. Annales des Mines - Responsabilité et environnement", vol. 61, no. 1, 2011, pp. 78-87
[114] United States Geological Survey (USGS), Mineral Commodity Summaries, 1994-2018.
[115] N.A.Mancheri, "World Trade in Rare Earths, Chinese Export Restrictions, and Implications", Resources Policy, No. 46, 2015, pp. 262-271.
[116] Seaman 2019, p. 17-18.
[117] COM(2017)490 final, p 7. Their "substitution index" exceeds 0.9, with 1.0 meaning absolute insubstitutability. Light rare earths are considered to be almost as insubstitutable.

main producer worldwide is South Africa, with Russia, USA and some other countries having minor deposits.[118] EU supply is provided by Switzerland (34%) South Africa (31%) United States (21%) and Russia (8%). As Switzerland is not a member state of the EU, the import reliance rate for PGMs is considered to be 99 %.[119]

Recycling has been identified as an effective method of reducing supply risk.[120] However, it cannot completely negate the dependency on virgin raw materials, not even in its most closed-loop form possible, due to several reasons. One of them is that the market demand growth for several CRMs outstrips the potential supply from discarded products – the demand for new products grows faster than old products are discarded.[121] Even currently the End-Of-Life Recycling Input Rate (EOL-RIR) of many CRMs is very low: 14 % for platinum group metals (PGMs), 8 % for HREEs and 3% for LREEs, [122] however, PGMs have a high EOL-RR but they do not have a high EOL-RIR simply because their demand is so high (as they also constitute a higher percentage of product mass).[123]

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[118] Johnson Matthey, PGM Market Report February 2020. <http://www.platinum.matthey.com/documents/new-item/pgm%20market%20reports/pgm_market_report_february_2020.pdf>(Accessed 22.2.2020.)
[119] COM(2017) 490 final, p. 5-7.
[120] British Geological Survey et al. 2017, p. 19. Also, European Commission Staff Working Document, Report on Critical Raw Materials and the Circular Economy [2018], SWD (2018)36 final, 2018, p. 10.
[121] In the context of REE-containing magnets, Jelle H. Rademaker, René Kleijn, and Yongxiang Yang, “Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling”. Environmental Science & Technology, 2013 47 (18), 10129-10136.
[122] COM(2017) 490 final, p. 7.
[123] EU Raw Materials Scoreboard 2018. For example, recycling rates for PGMs reaches up to 95% for certain product categories, such as industrial catalysts and 50-60% for automotive catalysts (which are by mass the category with the largest use of PGMs), yet PGM EOL-RIR stands at only 14 % due to the high demand. Also UNEP, *Recycling Rates of Metals – A Status Report* (UNEP, 2011), p. 18: “Where relatively high EOL-RR are derived, the impression might be given that the metals in question are being used more efficiently than those with lower rates. In reality, rates tend to reflect the degree to which materials are used in large amounts in easily recoverable applications (e. g., lead in batteries, steel in auto-mobiles), or where high value is present (e. g., gold in electronics). In contrast, where materials are used in small quantities in complex products (e. g., tantalum in electronics), or where the economic value is at present not very high, recycling is technically much more challenging.”

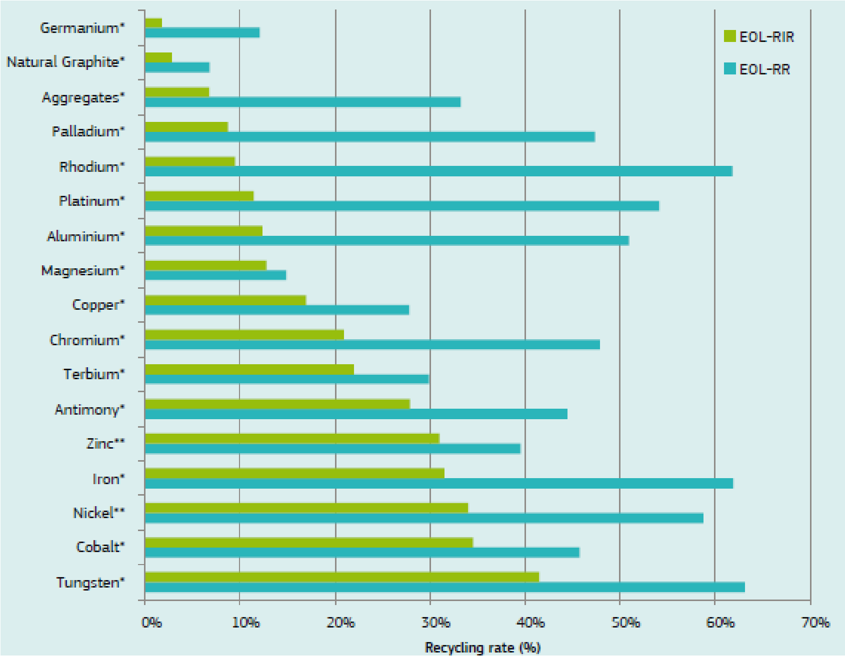

Figure 4: Comparison of recycling rates (EOL-RR) and recycling input rates (EOL-RIR) of certain materials.[124]

Second issue is that material losses during recycling are inevitable due to thermodynamical constraints, even when using all the best processes currently available. Though a significant amount of CRM losses during recycling phase are preventable with better recycling actions across the entire product life cycle (this issue is discussed further in sections 4 and 5), some happen due to the laws of physics, especially because those of thermodynamics (though advances in technology may reduce these losses in the future).[125] Therefore, recycling cannot be the sole solution for supply risk. It should be implemented in tandem with other strategies, such as finding technological solutions to substitute to less critical materials where possible and developing more sustainable mining technologies.

[124] EU Raw Materials Scoreboard 2018.
[125] See for example UNEP 2013, Section 3.2, The physical limits of "closed loop" recycling, and Hagelüken 2014, p 65-66. On wider thermodynamical limitations of metal recycling (due to which it may be impossible to attain 100 % effective recycling rate), Castro, M. B. G., J. A. M. Remmerswaal, M. A. Reuter,and U. J. M. Boin, A thermodynamic approach to the compatibility of materials combinations for recycling. Resources, Conservation, and Recycling 43: p. 1–19., 2004.

As a side note, tools for measuring the circularity (or lack thereof) of materials are important for measuring and developing policy effectiveness. Simple but effective[126] measurements are the aforementioned End-Of-Life Recycling Rate (EOL-RR), which measures the percentage of the material recovered from waste streams[127], and End-Of-Life Recycling Rate (EOL-RIR), which is measured by the percentage of the demand for the material that is satisfied by the use of recovered material.

[126] To a degree; these measurements suffer somewhat from, inter alia, the difficulties of defining system boundaries and insufficient reporting. See JRC Assessment of the Methodology for Establishing the EU List of Critical Raw Materials 2017, p. 57-63.
[127] For example, if a metal has a recycling rate of 50%, it means that 50% of its mass that is present in waste will be recovered.

4. Why the loop is not closed on CRMs in WEEE?

4.1. Introduction to the problem

4.1.1. General overview

There are several reasons for the low recycling rate of CRMs from WEEE,[128] including issues such as problems with collection of the waste, the preprocessing and separation of components within the scrap, the recycling targets that focus only on the mass of the recycled material, cost-effectiveness and lack of technology. However, some metals, including some CRMs, have a high recycling rate, as seen in Figure 2. These metals include platinum (CRM), palladium (CRM), gold, silver, cobalt (CRM) and tungsten (CRM). It is illustrative to discuss first shortly why these particular materials have high recycling rates. First, there are well established collection systems and processing routes in place for a number of devices and components, such as industrial catalysts (which contain platinum) and special alloys.[129] These systems have been built because the metals in question have high economic value whilst also being easily extractable from those components, and their life cycles are "closed" and therefore controllable.[130] This is not the case with most CRMs within WEEE. One of the greatest current barriers for CRM recycling in WEEE is that in most WEEE categories the majority of CRMs are in very low concentrations[131], and embedded within specific components within the discarded objects, which are difficult to remove with automaticized processes. If these components are not removed and sorted out prior to normal recycling processing, in many cases the materials they contain will be lost due to them getting mixed with other materials from which they can't be separated.[132] This is the usual fate of CRMs and rare metals in contemporary WEEE recycling, the exception being a fraction of the most valuable CRMs.[133]

[128] See Otmar Deubzer; Andrea Amadei; Giorgio Arienti; Luca Campadello; Witold Kurylak; Michail Samouhos, "Prevalence, recyclability, cost and financing of CRM recycling from WEEE, SCRREEN 2018, (SCRREEN D8.1) p. 6 and Hagelüken 2014 p. 48-50., and ERECON 2015, p. 7 for general overviews.
[129] SCRREEN D8.1 2018, p, 33.
[130] See Figure 8.
[131] Except for magnesium and antimony, the concentrations are far below 1%. SCRREEN D8.1 2018 p. 10.
[132] SCRREEN D8.1 2018, p. 45.
[133] SCRREEN D8.1 2018, p. 84.

It is important to understand the differences between the challenges in WEEE recycling and in the more commonly known waste streams, such as plastic bottles, glass or steel scrap. The recycling of latter is fairly simple because they consist of what Hagelüken calls “mono-substance” material compositions within simple products that are largely without hazardous elements. In contrast, WEEE recyclers must cope with “poly-substance” waste material[134], including hazardous materials, consisted of complex components within highly complex products.[135] As such, separating these materials from each other is a significant challenge, which drives up costs and raises the barriers of entry for recyclers.

The issues inherent in CRM recycling from WEEE are not being alleviated by current waste legislation. WEEE Directive aims to optimize material recovery via setting a mandatory level of reuse, recycling and recovery, which are set as mass percentages of total WEEE generated that must be reused or recovered. These targets are measured by dividing the weight of the WEEE that enters the recovery or recycling/preparing for re-use facility, after proper treatment, by the weight of all separately collected WEEE for each category, expressed as a percentage. Depending on the WEEE subcategory, these percentages vary between 50 and 85 %.[136] What this creates is an incentive to recover the “base” metals (and in many cases plastics) of the products, as they constitute most of the mass of WEEE[137].

Of note is also that as of now, insufficient actionable data on the material flows of the CRMs through the socio-economic metabolism hinder the attempts to improve the current situation.[138] While it is beyond this thesis’ scope to analyze the situation and suggest improvements, it should be noted that in the future when/if more detailed data comes available, more detailed and specific improvements can be made.

[134] An excellent example of this is the modern mobile phone, which contains over 50 different elements.
[135] Hagelüken 2014, p. 48.
[136] WEEE Directive, Article 11 and Annex V.
[137] UNEP 2013, Appendix B, "Details on Metals found in WEEE”.
[138] EN Horizon 2020, Work Programme 2018-2020: “Cross-cutting activities”, p. 50. <https://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-cc-activities_en.pdf> (Accessed 7.4.2020) and EU Raw Materials Scoreboard 2018, p. 69.

4.1.2. How WEEE is treated in End-of-Life recycling facility?

It is necessary to touch upon the techniques used in WEEE recycling in order to understand the technical problems of CRM recycling and why their recycling rate is currently low. The first step of WEEE treatment is, when applicable, manual dismantling and detoxification stage, where the potentially hazardous materials of the product are removed as per the requirements of WEEE Directive's Article 8 and Annex VII. These include, inter alia, batteries, printer toners, mercury-containing components, CFCs, printed circuit boards and liquids such as oils.[139] After this, certain components may be removed, but in this step there is massive variation in what kind of preprocessing there is, ranging from none to extensive.[140] There is a large variety of electronic devices (ranging from fridges and industrial machines to laptops and portable music players), so therefore applicable preprocessing varies significantly. In addition, the preprocessing can vary between facilities and collection schemes. The pre-treatment standards imposed by WEEE Directive are somewhat rudimentary, their main aim being to remove materials that are hazardous to environment and/or human health, and more ambitious recyclers may go significantly beyond them in order to improve the recyclability of the waste further downstream in the recycling process.

[139] SCRREEN D.8.1, p. 33.
[140] "None" may especially apply to recycling that is not compliant with legislative requirements, while "extensive" can apply for pilot programs such as one carried out by ECODOM: <http://www.criticalrawmaterialrecovery.eu/wp-content/uploads/2018/12/ECODOM-Recovery-case-study.pdf> (Accessed 10.3.2020).

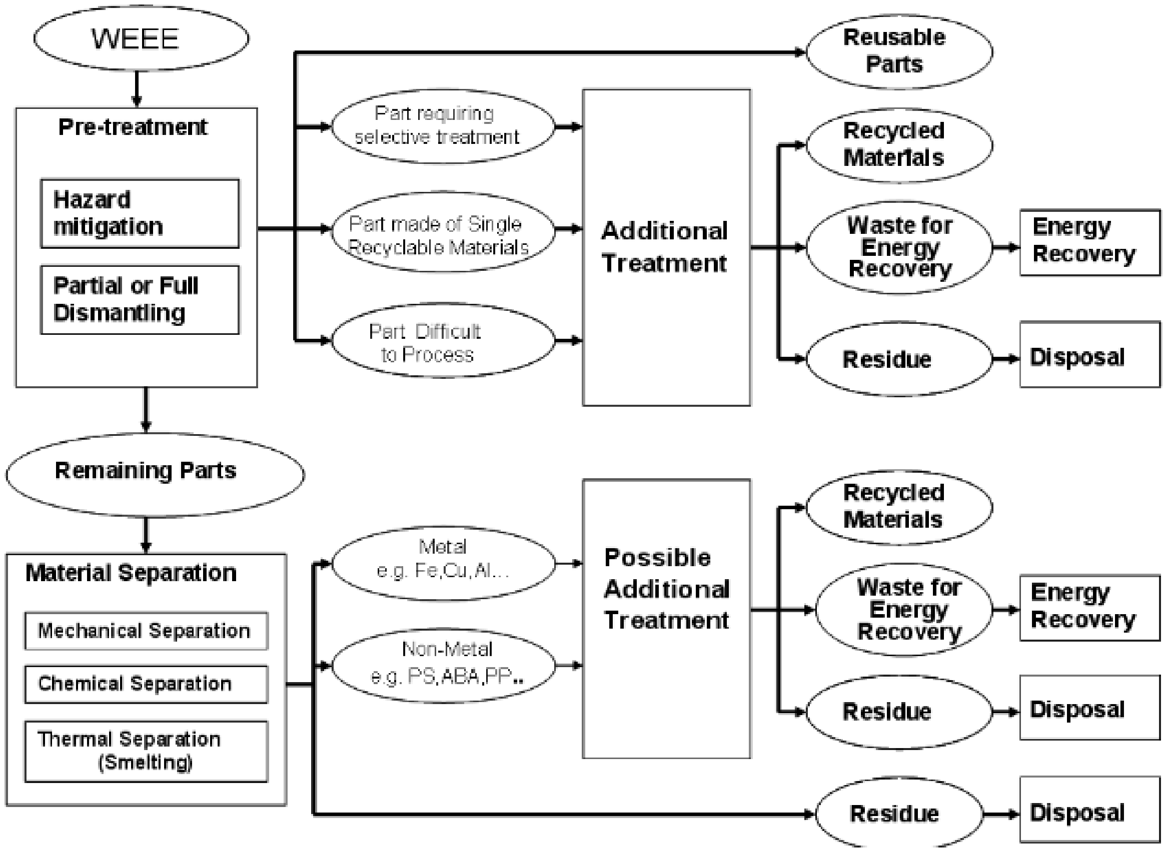

Figure 5: EoL treatment of WEEE according to IEC/TR 62635 standard.

After the desired components are removed, the remaining scrap is processed mechanically. In this process, generally the scrap is shredded into "pellets". The process of shredding is called "material liberation" ("material separation" in Figure 5). The purpose of this is to prepare the waste to be in the correct physical form for the next steps in the process. In the next phase the goal is to separate the different elements from the scrap for recovery. There are several techniques available, depending on the elements in question and the individual facility. Generally, there are either "wet" or "dry" methods: In wet processing, fluid is applied to the scrap so that it turns into sludge and physical properties of the materials, such as magneticism, conductivity and density, are exploited to separate the elements. In dry processing, the scrap is made into dust, which allows for, inter alia, magnetic, centrifugal or air-based separation, exploiting the differing weights or other properties of the materials.[141]

[141] Kari Heiskanen, "Physical separation 101" in Ernst Worrell, and Markus Reuter (eds.) *Handbook of Recycling : State-of-the-art for practitioners, analysts and Scientists* (Elsevier, 2014), p. 537-543. Also UNEP 2013, section 3.3.3.1, "Physical sorting processes".

However, there is (currently, at least) no process that can handle all the elements of the periodic table at once – if the shredded material contains an element that the recycling process used cannot extract, the unsuitable element will be lost for recovery – and there are many incompatible combinations.[142] One such example is printed circuit boards: Among other materials they contain *copper, precious metals, antimony, indium*, **tantalum, gallium, germanium and rare earth elements.** Due to thermodynamic constraints, only either *italicized* or **bolded** materials can be recovered, but not both groups.[143] For this reason, in certain cases prioritizations must be made and 100 % recovery will be an impossible goal. However, this problem can be negated to some degree with ecodesign (Section 5.3). In addition, advancements in technology can potentially alleviate the problem to a degree[144], but it must be kept in mind that predicting the directions of (economically viable) technological progress can be difficult.

As mentioned, there is some variance in processes used, depending on the available technology, priorities of the recycler and the quality of the waste stream, meaning the degree of sorting and separation done at the waste collection stage, which affects the homo/heterogeneity of the waste stream (generally the more homogenous the stream is, the more recyclable it is, as processes can be better tailored for it). The use of best available technology is especially important in the final processing phase, as informal processes lead to both material loss and possible environmental risks (due to material leaks).[145]

[142] Hagelüken 2014, p. 51-57, also Christian Hagelüken, “Recycling of electronic scrap at Umicore’s integrated metals smelter and refinery”, ERZMETALL, 2006,59 (3), 152–161, and UNEP 2013, section 3.3 “Incomplete material liberation from EoL products – A key reason of resource loss”.

[143] Hagelüken 2014, p. 58.

[144] Examples of new technologies that have the potential of creating new viable material mixes: Lahtinen, E., Hänninen, M. M., Kinnunen, K., Tuononen, H., Väisänen, A., Rissanen, K., & Haukka, M., “Porous 3D Printed Scavenger Filters for Selective Recovery of Precious Metals from Electronic Waste”. Advanced Sustainable Systems, 2 (10), 2018 and Arda Işıldar, Eric D. van Hullebusch, Markus Lenz, Gijs Du Laing, Alessandra Marra, Alessandra Cesaro, Sandeep Panda, Ata Akcil, Mehmet Ali Kucuker, Kerstin Kuchta, “Biotechnological strategies for the recovery of valuable and critical raw materials from waste electrical and electronic equipment (WEEE) – A review”. Journal of Hazardous Materials, Volume 362, 2019, p. 467-481.

[145] Figure 7 and UNEP 2013, section 4.3 “Final processing”.

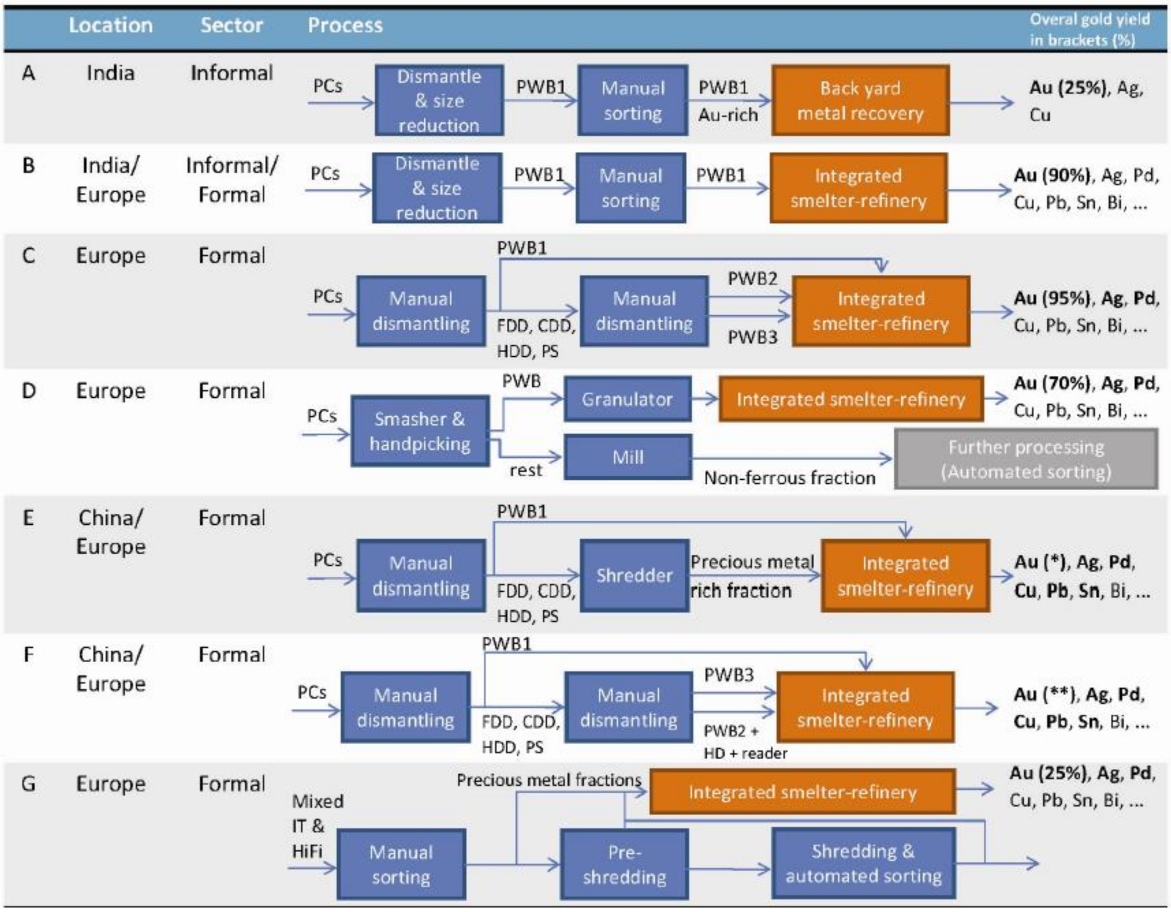

Figure 6: Different recycling processes used in the recovery of gold and other materials from PCs.[146]

4.2. Insufficient collection and pre-processing

As in the previous section has been preliminarily discussed, pre-processing is a key phase in WEEE recycling – if a high efficiency across several materials is desired, an efficient pre-separation of components with different material compositions is necessary in order to create highly recoverable mixes that do not have material incompatibilities. Pre-processing consists

[146] Meskers, Christina; Hagelüken, Christian, "The impact of different pre-processing routes on the metal recovery from PCs" in L.M. Hilty, H. Itoh, K. Hayashi, X. Edelmann (eds.): *R'09 Twin World Congress and World Resources Forum*, *Resource management and technology for material and energy efficiency* (EMPA Materials Science and Technology, St. Gallen 2009, ISBN: 978-3-905594-54-6).

both of collection (when control of the waste is transferred from the product owner to the waste collector) and pre-treatment (see Figure 5).

For example, in the case of mobile phones, in an ECODOM study it was found that when manual (high-quality) disassembly was applied to CRM-rich components in pre-processing, 90 % of CRM and metals could be sorted out in their separate components which in turn could then be effectively recycled. Meanwhile if only automatic pre-processing and material liberation is applied (meaning that the phones are fed whole into a shredder), the dissipation of CRMs and other metals in various streams was 60-90 %.[147] This is especially disastrous for REEs, which will be effectively unrecyclable in such a mix, mainly because their concentrations will be so low.[148] Another example is the crude mechanical separation of printed circuit boards, in which 85 % of the precious metals is lost.[149]

Currently the requirements on waste collection are, as mentioned previously, set in the WEEE Directive, and consist of a collection rate of 65 % of the average weight of EEE placed on the market in the three preceding years in a Member State, or alternatively 85 % of WEEE generated on the territory of Member State, and the collection must be done separately from municipal waste or other waste streams. The collection rate referred to in Article 7(1) does not set individual collection rates for specific product categories. This is problematic for the reason that targeted, separate collection of disposed CRM-rich products could significantly increase their recoverability.[150]

Currently, the main deciding factor for pre-processing quality is economics. Increasing dismantling depth (the fidelity of component separation) will improve the downstream recyclability of the waste as the materials become increasingly sorted, making them easier

[147] SCRREEN D8.1 2018, p. 45.
[148] Unless if titanic amounts of energy is spent in order to liberate the materials down to atomic level, which would be completely infeasible and unsustainable. See also, Kumari, Archana; Jha, Manis; Pathak, Devendra Deo, “Review on the Processes for the Recovery of Rare Earth Metals (REMs) from Secondary Resources”. In *Rare Metal Technology 2018*, p. 53-65, and Simon M. Jowitt; Timothy T. Werner; Zhehan Weng; Gavin M. Mudd, “Recycling of the rare earth elements”. Current Opinion in Green and Sustainable Chemistry, Volume 13, 2018, p. 1-7.
[149] Bachér, John ; Mrotzek, Asja ; Wahlström, Margareta, “Mechanical pre-treatment of mobile phones and its effect on the printed circuit assemblies (PCAs)”. Waste Management. 2015 ; Vol. 45. pp. 235-245.
[150] Batinic, Bojan & Vaccari, Mentore & V., Savvilotidou & Kousaiti, Athanasia & Gidarakos, Evangelos & Marinkovic, Tijana, “Applied WEEE pre-treatment methods: Opportunities to maximizing the recovery of critical metals”, 2017.

to recover in final processing stages. On the opposite side, each step of dismantling depth is an added cost.[151] In order to liberate many CRMs, including REEs, generally a high dismantling depth is required, however, due to their low concentrations, the value of recovering them is not, by itself, enough to offset the required steps of dismantling depth.

The root cause for this problem is the ever-increasing complexity and miniaturization of electronic products. The sheer number and form of the components, combined with the way they are embedded in the structure of the product, make it difficult to render the discarded product into a form where its materials can be optimally extracted.[152] This is because different metals are often concentrated in specific components of the whole product, which creates the need for extensive dismantling of the discarded products before they are further processed in order to reach a high recycling rate for all materials in the product. Finally, the material complexity of modern electronic products can easily create incompatible mixes of material. However, as mentioned, high-quality preprocessing is currently a cost-prohibitive, as it must (usually) be done manually, which results in high costs for labor, or at least so in EU.[153] Because of this, in developed countries the pre-processing of WEEE is done by automatic and mechanical means, even though its efficiency is far lower, as can be seen in Figure 7.

[151] Meskers and Hagelüken 2009, p. 4-5 and Gmünder, S., "Assessment of optimal manual dismantling depth of a desktop PC in China based on eco-efficiency calculations". M.Sc. thesis of EMPA and ETH Zürich, 2007.
[152] For example, Haque, Nawshad & Hughes, A.E. & Lim, K. & Vernon, Chris, "Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact". Resources. 3, 2014, p. 626.
[153] See for example UNEP 2013, p. 166, Figure 69, which illustrates the costs involved in the pre-processing of end-of-life vehicles. Current legislation (and state of technology) necessitate some manual dismantling of cars to increase the recycling rate, and manual labor forms by far the largest part of the costs of pre-treatment. Of note is that in China, manual pre-processing is used in formal WEEE recycling – however, the labour costs of a dismantling plant worker are roughly 20 times smaller in China than in Europe. *Gmünder 2007*.

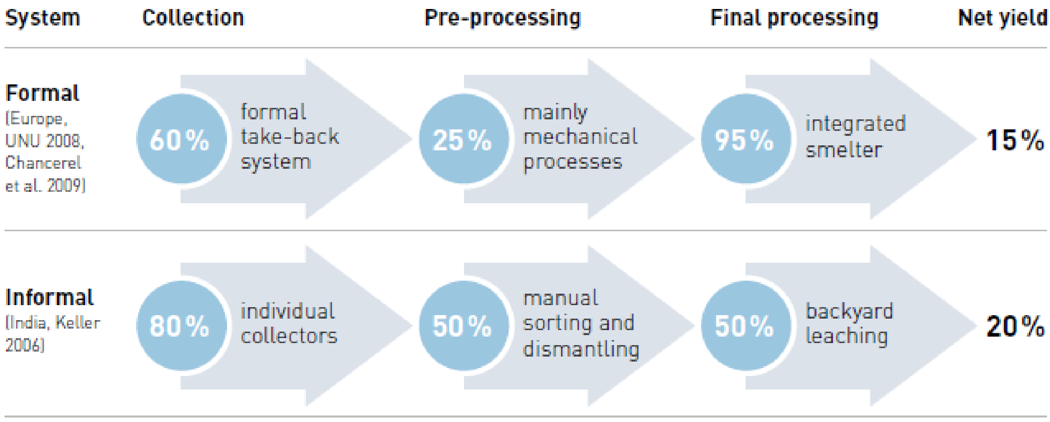

Figure 7: A comparison of WEEE gold recycling system efficiencies over different stages in Europe and India.[154]

The importance of high-quality pre-processing cannot be overstated (which includes both targeted collection of CRM-rich discarded products and extensive component separation). This is also in line what operators in the final processing business have reported in a SCRREEN feedback survey, who especially raised the need to separate the CRM-containing components from the waste stream.[155] The importance of specific collection also been noted in the new Circular Economy Action Plan, though the mention is in the context of all waste and in very general terms[156]. Targeted, specific collection with high sorting rates (different products are separated from each other as much as possible) is even more important in WEEE, due to the variance that products of different categories have (and in some cases even in the same product category, as defined in the directive's Annex III).[157]

[154] UNEP 2013, p. 125. Based on Chancerel, P., Meskers, C.E.M., Hagelüken, C., and Rotter, V.S., "Precious metal flows during the pre-processing of electronic waste". Journal of Industrial Ecology, vol. 13(5), 2009, p. 791 – 810, and Keller, M. "Assessment of gold recovery processes in Bangalore, India and evaluation of an alternative recycling path for printed wiring boards, a case study". See also Chi, X., Streicher-Porte, M., Wang, M.Y.L., Reuter, M.A., "Informal electronic waste Recycling: A sector review with special focus on China", Waste Management, vol. 31, pp. 731 – 742 (2011).
[155] SCRREEN - D8.2, p. 31-32.
[156] COM(2020) 98 final, p. 13.
[157] E.g. "Small IT and telecommunication equipment" contains products from mobile phones to portable calculators to printers, which differ significantly in material composition and dimensions.

Another problem concerning WEEE is that the effective collection rates of many product categories rich in CRMs (actual categories, not of the Directive's), such as smartphones, are too low[158], which leads to a supply problem, lowering the amount of usable material, which is an especially acute issue with CRMs, as their low concentrations in WEEE necessitate high level of collection to make their recycling viable – in some cases concentrations of the material are so low that a single facility could handle on a global scale all the final processing needs of the entire world. Collection is an extremely important phase in pre-processing (alternatively, it can be considered pre-pre-processing if one so wishes) due to the fact that it is the first phase in recovery. As illustrated in Figure 5, material losses in an earlier stage of recycling are exceedingly difficult to compensate for in the later stages, as all earlier losses compound downstream so that each successive step will have less material to work with. Even the highest quality final processing cannot make up for significant material dissipation and loss in the stages that precede it. Currently, roughly 50 % of WEEE is currently properly collected in EU[159]. This loss of material is not significant only by its mass: the low collection rate also means that the lack of supply makes recycling economically less attractive, reducing interest in developing new recycling projects and technologies.

Another issue relating to low collection rates is the prevalence of illegal WEEE processing and trade: According to Countering WEEE Illegal Trade (CWIT) project study, 35% (3.3 million tons) of all the e-waste discarded in 2012 went to the official recycling systems. The other 65% (6.15 million tons) was handled improperly relative to the standards of legislation. Recycling under non-compliant conditions and scavenging within EU's borders constitutes a major loss of material, and in both legal and illegal exports to outside EU's borders result in a significant loss of material (2.8 million tons in total)[160]. This is a significant problem: enforcement of WEEE legislation must be strengthened significantly to increase the amount of available material for recyclers. Majority of illegal exports will not be recycled efficiently or handled in environmentally prudent manner, and the reduced amount of available scrap

[158] Baldé, C.P., Forti V., Gray, V., Kuehr, R., Stegmann, P., *The Global E-waste Monitor 2017* (United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna), p. 72-75.
[159] Eurostat, "Waste statistics - electrical and electronic equipment, Waste electrical and electronic equipment, total collected", 2016.
[160] Countering WEEE Illegal Trade (CWIT), "Summary Report, Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap", 2015.

makes recycling less attractive for companies and investors. Recovery facilities for WEEE are significant investments and require a fair degree of certainty on availability of processable material for them to be feasible.

In summary, the main hurdle in the collection and pre-processing stage for WEEE recycling is that most modern electrical products are physically complex devices which need to be disassembled, especially for those components that contain CRMs, before treatment. Efficient disassembly would likely require targeted collection of different products, especially those that contain particularly high concentration of CRMs, so that tailored processes can be formulated for maximum efficiency. This issue is not currently recognized sufficiently in the current legislation. WEEE directive makes direct requirements on collection and disassembly, but required collection is based only on percentages of different products released on market, which is not sufficient for the needs of CRM recycling, and same applies for the requirements on disassembly, which are very basic and do not consider CRM-rich components. Necessary pre-treatment is not by itself economically attractive at the moment and the current legislation as a whole does not incentivize the actors in the field to consider CRM recycling in any way.

4.3. Recycling targets that are based on percentage of the total mass of WEEE

The WEEE Directive currently sets mandatory recycling targets that are based on a percentage of the material recovered from the total mass of the product.[161] The attainment of the recycling target is calculated via dividing the weight of the WEEE that enters the recovery facility (after proper treatment) by the weight of all separately collected WEEE for each category (which are set in Annex V of the Directive), expressed as a percentage. The targets vary slightly across different WEEE categories, from 75 % to 85 %, generally with larger equipment having higher recovery targets. This choice is most likely due to the fact

[161] WEEE Directive Article 11 and Annex V.

that larger equipment (such as freezers, washing machines and musical equipment[162]), tend to be more homogenous in their material composition.

However, as CRMs may constitute only 1 % of a device's weight or less, there is little incentive to recycle them unless they can be extracted easily (cheaply) – as things stand, there is almost no market drive for CRM recycling.[163] In addition, the recovery targets create specific demands for WEEE recycling technology and drives it down certain development paths[164], as developers of recycling technologies are encouraged to think first and foremost on how to recycle the base metals in large amounts in order to reach the mandatory targets, whilst giving no incentive to focus on the valuable materials of low concentrations which also may be difficult to extract intact.[165] Flat recycling rates do not take into account the properties of a poly-substance waste stream that contain wide plethora of materials that have different environmental, economic and technological impacts. The end result is something that cannot be described as high-quality recycling, which is a concept that the New Circular Economy Action plan emphasizes[166], though it does not define what it exactly is. Nevertheless, it likely does not include the near-complete failure to recycle CRMs, their environmental impact and importance being so significant.[167]

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[162] As a piece of trivia: pipe organs installed in churches are explicitly excluded from this category in the Directive.
[163] Hagelüken 2014, p. 47, SCRREEN D8.2, p. 30.
[164] SCRREEN D8.2, 2018, p. 84.
[165] Van Eygen, E., De Meester, S., Dewulf, J., "Raw materials savings by urban mining: the case of desktop and laptop computers in Belgium", Policy Research Centre for Sustainable Materials Management, Leuven 2015, p. 34; Henna Punkkinen, Ulla-Maija Mroueh, Margareta Wahlström, Lena Youhanan and Åsa Stenmarck, "Critical metals in end-of-life products – Recovery potential and opportunities for removal of bottle-necks of recycling". Nordic Council of Ministers 2017, p. 77; Jurate Miliute-Plepiene; Lena Youhanan, "E-waste and Raw Materials: From Environmental Issues to Business Models". IVL Swedish Environmental Research Institute, 2019, p. 27.
[166] "High-quality recycling" is mentioned 4 times in the 19-page document. COM(2020) 98 final.
[167] On what factors to consider when evaluatiing the quality of recycling, see Velis Costas; Paul H. Brunner, "Recycling and Resource Efficiency: It Is Time for a Change from Quantity to Quality". Waste Management & Research, vol. 31, no. 6, June 2013. The issues they raise are the importance of clear defnitions on what is considered "input" and "output" in a recycling system and that the different qualities of materials must be taken into account.

4.4. Waste hierarchy and its problems in context of WEEE

4.4.1. What is the waste hierarchy?

Waste hierarchy was introduced to the EU legislation via the 2008 Waste Framework Directive. It stipulates that when member states develop waste law and policy, they must keep in mind the hierarchy's priority order of what constitutes the best overall environmental option. Top priority is given to prevention of waste, followed by preparing for re-use, recycling and other recovery, including energy recovery. Least desirable is disposal and as such should be avoided whenever possible. The main goal of the hierarchy is to minimize landfilled or otherwise disposed waste.

Figure 8: The waste hierarchy visualized.[168]

4.4.2. The structure of the Waste Hierarchy

The highest step, "prevention", covers measures that are taken before material becomes waste. There are two forms of "prevention": quantitative waste prevention and qualitative waste prevention. Quantitative waste prevention includes actions that reduce the overall

168 European Commission, "Being wise with waste: the EU's approach to waste management". Luxembourg: Publications Office of the European Union, 2010.

quantity and mass of waste that is produced.[169] "Re-use" (which is qualitative waste prevention) means activities where products or components are used again for the same purpose for which they were conceived.[170]

"Recovery" is a key concept of WFD. "Recovery" means any operation of which the principal result is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy.[171] Recovery includes "preparing for re-use", "recycling" and "other recovery" portions of the hierarchy. The waste must gain an useful purpose as a "principal result" of the recovery operation for it to be considered recovery. Annex II of the WFD contains a non-exhaustive list of recovery operations, but the concept does not operate on numerus clausus principle: any operation that complies with the general definition of recovery (waste gains an useful purpose) will be considered recovery.

"Recycling" in the context of WFD means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes, with the exception of energy recovery (which is included in the lower-tier category of "other recovery"). Recycling differs from re-use in that in recycling waste material is processed in order to alter its physico-chemical properties, while in re-use the material is used "as-is".[172] Waste processing which end result is a material that will not become a "product" (does not yet fulfil EOW criteria,[173] but will once it undergoes further processing) would not be considered recycling, but pre-treatment prior to further recovery. Such an operation is considered "preparation prior to recovery or disposal" or "pre-processing" before full recovery.

Of note is that in the context of WEEE, the line between re-usable product (EEE) and waste (WEEE) is a key issue in export shipments of EEE and WEEE (Article 10 and Annex VI of WEEE Directive) – shipments of EEE are generally allowed as-is (as long as the exporter

[169] Guidelines on the interpretation of key provisions of Directive 2008/98/EC on waste [2012], p. 28.
[170] WFD Article 3(13).
[171] WFD Article 3(15).
[172] Guidelines on the interpretation of key provisions of Directive 2008/98/EC on waste [2012], p. 32.
[173] The criteria are: The substance or object is commonly used for specific purposes; a market or demand exists for such a substance or object; the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and the use of the substance or object will not lead to overall adverse environmental or human health impacts.

can sufficiently prove that the shipment indeed contains functional electronic equipment and upon delivery will be used as such), while shipments of WEEE must comply with additional requirements that concern hazardous waste (additionally, the exporter must be able to prove that the shipment will be treated in WEEE Directive-compliant manner).[174]

“Other recovery” is any operation that meets the criteria of recovery but fails to comply with the specific requirements for preparation for re-use or for recycling. This generally means “energy recovery”, which often takes the form of incineration or co-incineration of the waste as fuel or other means to generate energy.[175] In the context of WEEE recycling, plastics are often used in this manner to generate extra energy for the recycling process.

“Disposal” means any operation which is not recovery, even when the operation has as a secondary consequence the reclamation of substances or energy. The latter part effectively means operations where the incineration or other use of the waste results in some energy being recovered, but overall the gain is neglible. Other forms of disposal include landfilling the waste and other treatment where the material no longer plays a part in the economy.

In addition, according to the Article 4 of the WFD, Member States must take measures that result in the “best overall environmental outcome”. The articles allow for specific waste streams to depart from the waste hierarchy when it is “justified by life cycle thinking on the overall impacts of the generation and management of such waste”.

4.4.3. Waste hierarchy and Circular Economy – Working as intended or in need of a rehaul? In the context of CRMs and WEEE

Historically, the Waste hierarchy first came to be by national proposals (such as so-called Lansink's Ladder, which was proposed in the Netherlands in 1979 and implemented during

[174] Regulation (EC) No 1013/2006 on shipments of waste and Commission Regulation (EC) No 1418/2007 concerning the export for recovery of certain waste listed in Annex III or IIIA to Regulation (EC) No 1013/2006.
[175] However, if the operation does not meet the energy efficiency requirements set in WFD Annex II, the operation will be considered disposal.

the 90s).[176] On the EU level it was first implemented via communication from the commission in 1989[177] before finally being codified to legislation by the 2008 Waste Framework Directive. During the "formative years" of the waste hierarchy, namely in 1980s–1990s, the main concerns in waste management were landfill space and contamination (and cost of disposal).[178] These concerns were reflected in the structure of the hierarchy, which essentially aims to above all else divert waste from landfill.[179] The WEEE directive's recycling targets that are based on the percentage of total mass of waste seem to directly follow this mentality. Preamble 6 of the WEEE directive supports this, as it explicitly borrows the language of the hierarchy[180] to state its commitment to reducing waste as its "first priority", followed by the other steps of the hierarchy.[181]

Waste hierarchy is claimed to showcase "the best overall environmental option in waste legislation and policy"[182], though it does allow for departures from the order when necessary for "inter alia, technical feasibility, economic viability and environmental protection"[183]. However, these opportunities for departure have not been used in the context of WEEE, neither in the WEEE Directive or by the Member States.[184]

The main problem of the Waste hierarchy-mode of thinking in the context of WEEE, CRMs and Circular Economy is that the hierarchy cannot recognize the environmental impacts and technological importance of CRMs properly in WEEE stream, as it lacks the tools to do so. Waste hierarchy by itself cannot distinguish between open-loop and closed-loop recycling. In closed loop recycling, the material losses in different stages of the product life cycle are

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176 Stijn van Ewijk and Julia A. Stegemann, "Limitations of the waste hierarchy for achieving absolute reductions in material throughput". Journal of Cleaner Production, Volume 132, 2016, p. 3. Similar hierarchy was also adopted in the USA.
177 Communication from the commission to the council and the parliament: A community strategy for waste management [1989]. SEC 934 final. However, this was considered to be only a three-tier waste hierarchy.
178 van Ewijk and Stegemann 2016, p. 3. and Schall, John, "Does the solid waste management hierarchy make sense?: A technical, economic and environmental justification for the priority of source reduction and recycling". School of Forestry and Environmental Studies, Yale Univ., 1992.
179 van Ewijk and Stegemann 2016, p. 3-4.
180 By the use of words such as *re-use, recycling and other forms of recovery.*
181 "[A]s a first priority, the prevention of WEEE and, in addition, by the re-use, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste and to contribute to the efficient use of resources and the retrieval of valuable secondary raw materials".
182 WFD Directive, Preamble 31.
183 WFD Directive Article 4.2 and Preamble 31.
184 The Article 4.2 of WFD gives the Member States the right to depart from the hierarchy if they deem it necessary in the case of specific waste streams.

minimized, keeping the material "within the loop". In open-loop recycling, dissipative losses of the material happen during recycling. An example of this is the aforementioned issue of an element within WEEE that is processed by a metallurgical method that does not allow for its recovery. In this case, "some" recycling is happening, in the case of those metals that the process can extract, but the circle is far from complete. However, this is still considered "recycling" as far as the WEEE directive is concerned, because the recycling calculations are "input-based" rather than "output-based".[185] The reason for this is that according to the Commission, "valuable materials, which are present in significant amounts in WEEE, *are already almost completely recycled* due to their economic value, total output-based targets may only have a limited influence on actual recycling practices"[186] (emphasis mine), which is, as has been shown, completely wrong.

Material dissipation is not such a major issue in simpler ("mono-substance") waste streams, which is likely one reason why the waste hierarchy-mode of thinking has not been designed to take the issue into account, in addition with the fact that it was designed long before circularity and material efficiency became the important policy issues that they are now.

There is a need to evaluatively investigate the hierarchy in how it promotes Circular economy goals (or fails to do so) in the context of a poly-substance waste streams such as WEEE. As of now, the infallibleness of its the priority order may be accepted too much as gospel.[187] The waste hierarchy is functional as a general framework, and especially so if the goal is simply to reduce landfilled waste, but it requires more nuanced methods of assessment on what is the most environmentally prudent and materially efficient course of action. In particular, it needs a method to assess the efficiency of recycling in a materially complex waste stream. In WEEE, the efficiency of recycling cannot be determined simply

[185] "Input-based" means that material is considered recycled when it enters the recycling plant, while output-based means that only the materials that are recovered in the plant are considered recovered. Input-based measurements are preferred mainly because limited data exists on output streams, compared to input streams. See next cite note.
[186] Report from the Commission on the re-examination of the WEEE recovery targets, on the possible setting of separate targets for WEEE to be prepared for re-use and on the re-examination of the method for the calculation of the recovery targets set out in Article 11(6) of Directive 2012/19/EU on WEEE, COM/2017/0173 final, section 4.0.
[187] For example, according to Communication from the Commission on Towards a circular economy: A zero waste programme for Europe [2014], SWD(2014) 206 final, p. 5: "Some EU policies and instruments already provide tools and incentives in line with the circular economy model. The waste hierarchy that underlies our waste legislation is leading progressively to adoption of the preferred options of waste prevention, preparation for reuse and recycling, and discourages landfilling."

by the percentage of the mass of the waste that avoids landfill – the environmental (and economic) impacts of the recycling of different materials need to be investigated separately in order to drive recycling towards materials where the benefits of recycling are the highest.

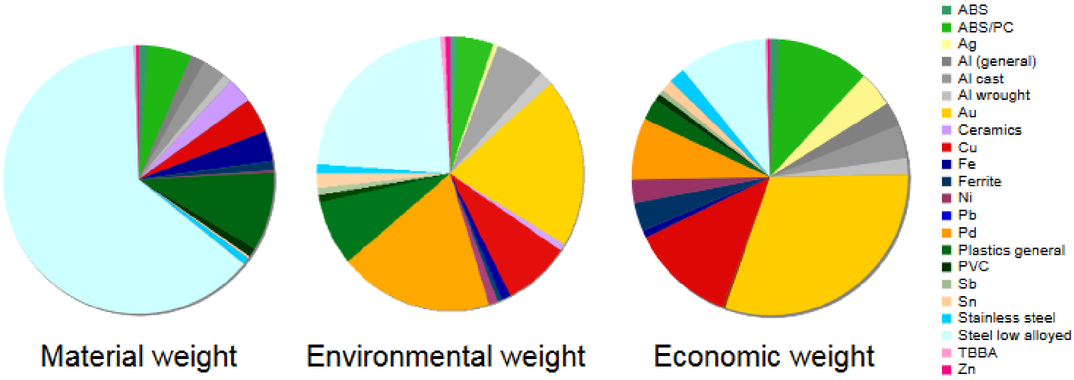

Figure 9: Comparison of Material weight, Environmental weight and Economic weight of materials used in personal computers.[188]

As has been said, Waste hierarchy model by itself cannot separate between the quality of recycling – when the waste enters a recycling facility, it is considered to be recycled, and it ignores the different impacts of materials that the figure above showcases. This is what van Ewijk and Stegemann mean when they say that waste hierarchy is not optimal for minimizing environmental impacts and natural resource use and for reaching dematerialization goals.[189] Another example of the problems of the hierarchy is the exports of used WEEE (both legal and illegal)[190] to Africa and other poor areas. They create a major loss of usable material – in fact, almost as much WEEE is exported yearly as is recycled properly (2.8 million tons vs. 3.3 million tons)[191]. While the re-use of old, used electronics is commendable per se, in most cases once the products reach the end of their (new) life, they will be discarded in linear economy fashion. In the waste hierarchy this is, somewhat perversely, a preferred result, as re-use is always prioritized over recycling (if the exception

[188] From Gmünder 2007.
[189] van Ewijk and Stegemann 2016, p. 6.
[190] Basel Convention prohibits WEEE exports if certain requirements are not met. One such requirement is that the waste must not be hazardous; this is not often the case with WEEE due to the substances that it contains. Dealers circumvent this by masking the waste as re-usable product.
[191] Countering WEEE Illegal Trade (CWIT) Summary Report, Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap. 2015.

granted by Article 4.2 of WFD is not used).[192] In the context of EEE, re-use is always only a temporary solution (the same does apply to nearly every product, but this is particularly so for EEE due to the usually short life cycle of products which is caused by rapid technological advancement causing obsolence), and all the products need to be recycled sooner rather than later.[193] For this reason the recycling phase is so crucial, as it is essentially the only way by which material from old products can be returned to the economy as new products.

The factors visualized in the above figure must be properly taken into account before an assessment on the impact of different recycling approaches is made. This is tied to the issue of recycling targets based on a percentage of the mass of waste. The focus must be shifted from material weight to environmental and economic weights, as this would be more conducive for the goals and ideals of Circular Economy. In addition, the quality of actual recycling that is happening must be submitted to far greater scrutiny. While these issues may fall outside the strict meaning of the Waste hierarchy (as it forms only the general framework of waste treatment), these issues highlight the need to develop a more nuanced view to waste treatment than what the current framework provides. The end goal of any waste policy must be material efficiency (in addition with minimizing environmental and health hazards), and Waste hierarchy requires better tools than it currently has to promote it optimally.

[192] Hagelüken 2007, p. 9-10.
[193] Of note is also that newer electronic products nearly always tend to be more efficient, creating more value while expending less energy.

5. Steps in order to close the loop on CRMs in WEE

5.1. Recognize the issue in legislation

Currently, the issue of CRMs is not even addressed in the current legislation: neither the WFD or WEEE Directive even mention critical raw materials. Mentions to resource efficiency are on a general level, such as WEEE Directive's stated goals to "reduce the disposal of waste", "contribute to the efficient use of resources" and "improve the environmental performance of all operators involved in the life cycle of EEE".[194] Similarly to WEEE Directive, WFD does not mention CRMs and conflates resource efficiency with percentage of waste's weight recycled.[195] This suggests that CRM recycling has not been considered at all during the drafting phase of the legislation, and as such the first step for the EU legislator to improve CRM recycling would be to explicitly recognize the issue and then proceed to create written legislation, both on the level of directive preambles and articles, that targets specific issues of CRM recycling.

Revision of WEEE directive has been slow: the directive was first implemented in 2002, revised in 2012, and some additions were made in 2018[196]. In context, the first list of EU critical raw materials was published in 2011 and policy relating to them has advanced significantly since them. For Circular Economy, the first EU action plan was published in 2015. As such, neither of these initiatives came into consideration when drafting the current WEEE Directive. This highlights the need for revision where new policy developments are implemented into the legislation. In this process data from the effects of the current legislation must be used to address specific problem areas of CRM recycling (and circularity and resource efficiency in general).

Stepping back to a higher-level view for a moment, it must be constantly kept in mind that CRM recycling is not a goal in itself, but one of the sub-factors of overall resource efficiency and Circular Economy. Measures taken to improve CRM recycling must result in a net

[194] WEEE Directive, Preamble 6.
[195] WFD Article 11. As we know by now, resource efficiency is a rather more nuanced issue.
[196] Directive (EU) 2018/849 of the European Parliament and of the Council of 30 May 2018 amending Directives 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment. Of note is that in this revision the change from input-based to output-based recycling rate was considered (Section 4.4.3., cite notes 185 and 186).

benefit for resource efficiency, but measuring the impacts of different actions is not a straightforward task. Recycling targets must be a mixture of a balanced consideration between environmental, economic and resource aspects. In addition, there must be a predetermined agreement on what the higher level goals are, so that the balance of different aspects can be rationally discussed. These considerations must also involve the potential negative side effects of different policy choices.[197] A simple example of this are the short-term costs of improved recycling: without technological advances, the recycling of many CRMs is not currently profitable, so increasing CRM recycling will inevitably come with added costs, even if in the long-term they would turn net positive. An evaluation matrix is needed when balancing positives against negatives. What is considered "optimal" solution also is partly a political choice: acceptable tradeoffs between different aspects are not clear-cut (recycling no matter what the cost is not "sustainable" either). However, externalized costs must be detected wherever they happen. Optimization that balances multiple policy goals (environmental savings, supply risk reduction, economic benefits and costs, etc.) is needed to synthesize the different aspects of a recycling policy and to create a system that is robust enough to handle such a dynamic area of human action. In addition, a balancing act between regional, continental and global concerns must be sought.

As for measuring recycling in the context of WEEE, material flow analysis is a very important tool in measuring and quantifying the actual recycling that happens in a recycling system and in tracking of actual resource efficiency with different materials.[198] Currently, the way recovery rate is measured may allow for materials to be considered recycled even though they do not re-enter the economy in any form (not even energy).[199]

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[197] On the necessity of clear goals and the importance of reliable measurements on positives and negatives of different policy options: Velis Costas; Paul H. Brunner, "Recycling and Resource Efficiency: It Is Time for a Change from Quantity to Quality". Waste Management & Research, vol. 31, no. 6, June 2013, p. 539–540.
[198] *Ibid*.
[199] See section 4.4.3. Also for example Till Zimmermann; Stefan Gößling-Reisemann," Critical materials and dissipative losses: A screening study", Science of The Total Environment, Volumes 461–462, 2013, parts on dissipation into other material flows. Even if such dissipation happens during the recovery phase, from WEEE Directive's point of view even the dissipated materials are recycled, as per Article 11 WEEE is considered recovered when it "enters the recovery or recycling/preparing for re-use facility" (input-based recycling rate).

5.2. Extending Extended Producer Responsibility

Extended Producer Responsibility (EPR) is defined as the extension of producer's responsibility of the product into the post-customer stage of product life cycle. The purpose of EPR is to reduce the burden of waste management on municipalities and to incentivize the producers to take environmental concerns into account when designing their products.[200] The end goal is to internalize the costs of environmental impacts and waste management to the price of products.[201] EPR is utilized for many different waste streams and the responsibilities it places on producers vary. For WEEE, producers have financial responsibility and full organisational responsibility for post-consumer stage. In practice, generally the EEE producers subcontract professional waste collection and treatment operators to complete their given responsibilities for collection and recovery. These arrangements are often organized into collective producer responsibility organisations.[202] However, there is some variance in how different aspects of EPR are handled in different Member States, as the collective producer responsibility schemes function on a national level – and some national schemes are more ambitious than others about recycling.

One challenging aspect for implementing effective EPR for WEEE is the fragmentation of the field. As noted by Wilts et al., there is no actor that is present in every part of the life cycle of electronics, creating a responsibility problem – as the popular saying goes, shared responsibility is no responsibility, and there is currently no actor that has the responsibility or the incentive for the entire life cycle to work with high material efficiency. And due to the properties of the field, creating such actors would be challenging to say the least.[203] This

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[200] OECD, *Extended Producer Responsibility: A Guidance Manual for Governments* (OECD Publishing, Paris, 2001), p. 9.
[201] *Ibid*, p. 17.
[202] European Commission, *Development of Guidance on Extended Producer Responsibility (EPR), Final Report* (EU Publications, 2014), p. 79.
[203] "Given the increasing complexity of products and the variety of production steps and materials used, the question arises who actually would take responsibility for the fate of these substances. As there is and will be no single person or institution who owns processes and produces throughout the whole cycle of extraction, production, consumption, recycling, and disposal, the question is how responsibility for a systems-wide sustainable management can be attributed to the actors along the chain in a way that favours sustainable management of the substances involved". Henning Wilts; Stefan Bringezu; Raimund Bleischwitz; Rainer Lucas; Dominic Wittmer, "Challenges of metal recycling and an international covenant as possible instrument of a globally extended producer responsibility". Waste Management & Research 29(9) 902–910, 2011, p. 905.

needs to be considered when designing regulation for WEEE recycling. Most important take-away from this[204] is that regulations need to be targeted towards a specific actor of a life cycle phase, and their properties must be considered when shaping their responsibilities. Producers have different tools to respond to regulatory requirements than the waste collectors and the recovery plant operators. In addition, attempts to encourage dialogue between the stakeholders should be made whenever there is an opportunity to do so (though this is an issue that in many cases goes beyond legislation).

Setting up the targets and goals of EPR is important. Generally, producers will choose the cheapest option possible that will allow them to complete their responsibilities[205], and this should always be kept in mind when designing EPR responsibilities. Furthermore, the unique characteristics of the waste stream should be taken carefully into account.[206] As WEEE as a waste stream is defined by, inter alia, poly-substance composition that varies significantly across product categories, challenges in the collection phase where mixed collection of different product types often lead to material losses in recovery phases[207], and CRM content which also varies between different product types, the responsibilities given to actors should be designed around those problems. The current EPR designed for WEEE fails to cover these issues, as it effectively consists only of a collection rate, based on a percentage of total products, and recovery rate, based on a percentage of a mass of products.[208]

Based on these factors it seems that to achieve higher CRM recycling rates, EPR should be extended in various ways so that the producers and their associates in the life cycle of electronics have not only collection and flat recovery responsibilities, but also responsibilities of material efficiency which take the criticality of the materials that they use in their products into account, thus bringing the EPR scheme in WEEE closer towards the ideals of Circular Economy. In the following sections the current bottlenecks of CRM recycling related to deficits in EPR are be discussed in more detail.

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[204] Ibid.
[205] Peter Beyer, Norbert Kopytziok, *Abfallvermeidung und –verwertung durch das Prinzip der Produzentenverantwortung*, [Prevention and recovery of waste by the principle of extended producer responsibility] (Österreichische Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft. Berlin, 2005).
[206] OECD 2001, p. 28.
[207] Section 4.1.
[208] Technically, achieving the collection and recovery rates are the responsibility of Member States, but effectively they are the targets that the producers (or their collective recycling schemes) must strive towards.

5.3. Solving the problems of collection and preprocessing

5.3.1. The need for high-quality pre-processing

In one case study on end-of-life mobile phones it was found that if manual disassembly is applied in pre-processing, 90 % of CRMs and metals can be sorted out in separate components, whereas when automated mechanical pre-treatment is applied, the dissipation of CRM and metals in various streams can be between 60 to 90 %.[209] As there is no economical incentive (due to the high labor costs) to dismantle WEEE manually in the EU or to develop automaticized high-quality component removal solutions, it seems necessary to introduce a regulatory push that requires or incentivizes the EPR schemes to introduce high-quality pre-processing of WEEE.

As mentioned previously in Section 4.2., the shredding and smelting techniques used in WEEE recovery processes can cause significant material losses if elements have been mixed to the point where effective separation becomes impossible. Because of this, it is necessary to dismantle components from the discarded products and then separate them based on their mineral contents so that a proper final processing can be applied for each material group. With effective preprocessing of the waste into CRM-rich and non-CRM-rich streams, the loss of CRMs can be lowered significantly. This has been confirmed in several case studies and trials done by the Italian WEEE collection consortium ECODOM. In one trial run it was found that such preprocessing resulted in a general recovery increase of 102% of gold, 29% of silver and 42% of platinum group metals compared to a normal mix without targeted pre-processing.[210] These trials show the importance of targeted collection of WEEE streams that contain CRMs, and that significant improvements can be made with fairly simple and cost-effective actions.[211] As has been mentioned, currently there is very little incentive to innovate

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209 SCRREEN 2018, p. 45.
210 ECODOM, Recovery case study <http://www.criticalrawmaterialrecovery.eu/wp-content/uploads/2018/12/ECODOM-Recovery-case-study.pdf > (Accessed 10.2.2020).
211 *Ibid.* Also for other collection trials, see Critical Raw Materials Recovery Project, "Collect More, Collect Better: Presentations from CRM Recovery projects trial partners across Europe who have developed innovative methods to collect WEEE and recover CRMs". <http://www.criticalrawmaterialrecovery.eu/wp-content/uploads/2019/02/A-Second-LIFE-for-Critical-Raw-Materials-Collect-More-Collect-Better-Slides.pdf> (Accessed 20.3.2020). See also cite note 146.

to increase CRM recovery, so it is somewhat safe to assume that in this stage of the product life cycle there are several “low-hanging fruits” which can increase material efficiency. Stakeholders in recycling business have also raised the importance of CRM component removal in interviews conducted by SCRREEN.[212]

Optimally, in the context of all recycling (and not just WEEE and CRMs), different types of waste would be collected separately based on their material content, then their components would also be separated and sorted based on their material content, and then the separate components would be sold to processing plants that specialize in the materials that those specific components contain.[213] In the context of CRMs, at least the product categories containing the highest concentrations of CRMs should be identified for separate collection.[214] This could be implemented via existing legal mechanisms by increasing the fidelity of product categories as defined by WEEE Directive[215] and extending EPR even further to include targeted, high-level collection and preprocessing of those product categories. Increasing the fidelity of product categories within the Directive is essential, because currently for example mobile phones (an excellent source of CRMs) have been placed in the same category such as printers (low CRM product), and computer mainframes are lumped with washing machines (another example of high-CRM product type categorized with a low CRM product).[216] As said, CRM-rich product types currently do not have any requirement for separate collection – the only requirement is separate collection of all WEEE in general[217]. Additional separate collection requirements for CRM-rich EEE product categories could significantly increase the downstream recyclability of those products. To summarize, pre-processing is intrinsically tied with collection – targeted, high-quality collection is in most cases necessary to facilitate high-quality component separation, as a homogenous stream is far more efficient to dismantle.

Currently the WEEE directive already includes some selective treatment and pre-processing requirements, such as the removal of mercury containing components, batteries and printed circuit boards[218]. These requirements do not seem to be designed for material efficiency, but

[212] SCRREEN D8.2, p. 32.
[213] Hagelüken 2014, p. 51-54.
[214] Batinic et al. 2017.
[215] Directive 2012/19/EU, Annexes III-IV.
[216] Directive 2012/19/EU, Annex IV.
[217] Directive 2012/19/EU, Article 5.
[218] Directive 2012/19/EU, Article 7, 8 and Annex VII.

to remove hazardous materials from the waste, reflecting how the primary focus of waste management has been on minimizing enviromental risk and reducing landfill (Section 4.4). Achieving the current goals of Circular Economy would likely require additional requirements. However, when considering what kind of pre-processing requirements should be set via legislation, the end goal should always be kept in mind, which is getting target materials into their proper treatment stream in order to maximize material efficiency – mandatory removal of certain parts should not be a prescriptive legal requirement as of itself.[219] Therefore, care should be taken in order to not introduce requirements that are laborious to fulfill but do not effectively increase recyclablilty. Robustness and flexibility are the main attributes that these requirements should have so that they would have the desired effect.

As mentioned previously, currently the barrier for increasing the quality of preprocessing are the costs, which would currently outweigh the value of extracted metals. If EPR is extended to include high-quality pre-processing, it would raise costs of electronic products[220] (at least in the short term), but this could be seen as acceptable trade-off due to several reasons. One of them is the "criticality" of the CRMs – improved recycling will reduce supply risks. Another is that currently the producers and consumers of electronic products within the EU effectively externalize the environmental risks involved in the mining of virgin CRMs, so there could be said to be a moral obligation on the EU to reduce the burden on the CRM producer countries and bear the costs involved in such actions.[221]

However, high-quality pre-processing is not synonymous with manual pre-processing, as the following section will show.

[219] Christian Hagelüken, "The challenge of open cycles – Barriers to a closed loop economy demonstrated for consumer electronics and cars". Conference paper, 2007, p. 4.
[220] SCRREEN D8.1, p. 85. " If the recycling of CRMs shall become common practice, e.g. by regulations – where processing technologies are available, the additional cost will have to be compensated in the course of the extended producer responsibility, taxes or from other sources".
[221] As CRMs used in electronics are mined almost exclusively outside of EU, see section 3.2.2.

5.3.2. The case of Apple and Daisy – automatized high-quality preprocessing

Daisy is a disassembly robot designed by Apple to dismantle its iPhone product line. It is specifically designed to remove the CRM-rich components (among others) from the end-of-life product, and it can operate at the rate of 200 phone disassemblies per hour. Once the components are removed, they are sold to recyclers who have the ability to extract the CRMs from the components.[222] This results in significant CRM recovery rate gains compared to "traditional" WEEE recycling. The solution is innovative in the sense that here the producer takes an active part in the pre-processing of the discarded product, instead of outsourcing it for collective EPR schemes. In this way, the pre-processing method and component removal can be tailored for the specific product, increasing efficiency significantly compared to "bulk" pre-processing where various EEE from many different manufacturers with different specifications are mixed together.

The roboticized pre-processing is combined with a collection method in the form of a trade-in scheme where product users can return their product to gain credit in return (which can be spent on the producer's products)[223], which resembles the deposit scheme currently in use in some countries for plastic bottles. Of note is that incentivized trade-in has proven to be an effective collection method in several contexts[224], and it can work particulary well with consumer electronic devices, as this method direcly leverages one of the issues of consumer electronics – their short life cycle[225]. This system also avoids some of the inefficiencies that often happen when collection and pre-processing are handed to a subcontractor, as greater synergies can be made to increase material efficiency when the production stage, collection stage and pre-processing stage can be orchestrated to support one another. The end result is a mixture of several aspects of high-quality recycling that the following sections discuss in

[222] Apple, "Environmental Responsibility Report 2018", p. 22.
[223] Electronics Takeback Coalition, "Apple's Takeback Program – Details about Apple's Takeback Program" <http://www.electronicstakeback.com/how-to-recycle-electronics/manufacturer-takeback-programs/apples-takeback-program/> (Accessed 3.4.2020).
[224] Such as the aforementioned deposit system used with plastic bottles. Promising results have also been achieved with WEEE. See Critical Raw Materials Recovery Project, "A Second LIFE for Critical Raw Materials event, Impact & Policy: Presentations summarising project impacts and policy recommendations." <http://www.criticalrawmaterialrecovery.eu/wp-content/uploads/2019/02/A-Second-LIFE-for-Critical-Raw-Materials-Impact-and-Policy-Slides.pdf> (Accessed 22.3.2020).
[225] Mobile phones in particular have had quick technological progress in the last decades, which has shortened product life-cycles as consumers often change to a newer phone due to its higher technological sophistication, and not because their previous one has become worn from use.

more detail, as it combines eco-design (section 5.5), targeted collection (5.4.2) and high-quality pre-processing (5.3.1). It is an example of precisely the kind of innovation that the WEEE legislation should strive to promote, facilitate, and even require.

Though it must be recognized that not all producers have the resources or the market presence to create schemes with similar solutions, as the saying goes, “necessity is the mother of innovation”. CRM recycling from WEEE is still in its infancy, especially on the producers side of the table, and this scheme showcases how resource efficiency gains can be made when producers invest in the recyclability of their products with a life cycle perspective.

5.3.3. Summary

By definition, “high-quality pre-processing” means, based on previous sections, pre-processing where the disposed product is dismantled in such a way that maximizes its recyclability downstream in the recycling process. There are “many ways to skin the cat” to increase the efficiency of processing, but due to the complex and often miniaturized physical form of the products, either human labor (manual pre-processing) or high technology (automated dismantling robot and similar solutions) is needed to achieve this. Both of these would increase the expenses of EPR schemes, but it must be noted that as current recycling targets being what they are, there has been little incentive for producers and collection & pre-processing schemes to optimize their pre-processing operations for maximum efficiency. Therefore it is reasonable to assume that the costs caused by the new requirements would go down over time as producers and collective recycling schemes would find innovative ways to increase efficiency. In addition, it is safe to assume that this activity would have economical benefits in other areas as companies would have to invest in R&D, and possibly create new jobs in the recycling sector.

It is beyond the scope of this thesis to offer detailed suggestions for pre-processing legislation, as the issues involved are too complex to address thoroughly here. As has been mentioned, pre-processing requirements need to be flexible, robust and effective, and to design such requirements, further studies are required. What this section has shown are the key considerations that must be taken into account when designing pre-processing requirements targeting CRM recycling.

5.4. Improving recycling targets to consider CRM recycling

5.4.1. Move away from recycling and recovery targets that are based on a percentage of the total mass of products

As was discussed in section 4.3, recycling and recovery targets based on percentage of weight of discarded products do not work as intended with poly-substance waste streams where the properties and relative concentrations of different materials can vary widely. The issue becomes especially prominent when some of those materials are critical raw materials that consitute only a small percentage of the mass of the product.

As seen in Figure 9, the disrepancies between the mass of materials in a product relative to their environmental and economic impacts of materials can be very large. And as has been discussed in the section on Critical Raw Materials, the importance of these materials cannot be measured only by their pure economic value either, as supply risks associated with them, combined their status as "keystone"[226] material in many technologies, make them "punch above their weight" in terms of criticality. And as has been discussed in section 4.0, the recycling of CRMs from WEEE is not economically viable by itself. Considering all the abovementioned issues, it appears necessary that in order to ensure CRM recycling it should made mandatory via legislation, as it seems very unlikely to happen "organically" via market forces, but at the same time is significant enough as an issue to warrant it.[227]

Somewhat frustratingly, the Commission examined the efficacy of the current recycling targets model from CRM recycling and Circular Economy goals perspective in 2017, but did not find any reasons for changing them, citing how setting treatment standards would be

[226] "Keystone" as in "keystone species".
[227] The current situation can be described as a form of "market failure", where economic forces fail to produce results in accordance with the public interest, necessitating regulation to step in. See for example Baldwin, Robert, Cave, Martin and Lodge, Martin. *Understanding Regulation: Theory, Strategy, and Practice* (2nd edition, Oxford, 2011), p. 15.

more efficient.[228] The underlying logic may not stand up to scrutiny, as they refer to how WEEE entering the collection schemes is usually being recovered/recycled at high rates *in terms of its weight* as an indicator of the current system's efficiency. That is beside the point however: The fact remains that CRM recycling is currently very low, despite the fact that the recycling targets are met in many Member States. What it in fact shows is how effective a mandatory CRM recycling target could potentially be – as the saying goes, "what gets measured gets done".

Mandating CRM recovery can be done via different approaches. One of them is creating mandatory recovery targets for each material, e.g. 50 % of REEs put onto market in EEE each year must be recovered, with percentages set for each CRM. However, this would require careful consideration on what the specific recovery targets for different materials would be, as the context where the materials are used can vary widely. For example, the materials that already have high recycling rate, such as tungsten, are characterized by "closed loops" across their entire life cycle. A life cycle closed loop[229] means that the product is kept whole and intact during its entire use by its user, then returned as-is for recycling. This is a characteristic of Business-to-Business sales of different forms of industrial machinery – and tungsten is used in machine tools. [230] In contrast, consumer electronics are characterized by "open loops" where losses of material happen across the product life cycle and their end-of-life collection is often incomplete. As such, the different life cycles of materials would have to be taken into at least some account, as a smaller user base of physically larger products is much more efficient for the ease of recovery. The market conditions and use of different materials, combined with their extractability (how efficient the BAT process for their

[228] "Overall, strict implementation, enforcement and monitoring of WEEE collection targets have a strong impact on actual recycling/ recovery, as it has been shown that WEEE entering the collection schemes is usually being recovered/recycled at high rates in terms of its weight. In the Circular Economy Action Plan, the Commission set out to promote the development of European standards for material-efficient recycling of WEEE, as well as of waste batteries and other relevant complex end-of-life products, to increase recycling of critical raw materials. This is considered a more pragmatic approach than setting binding output-based recycling targets." Report from the Commission on the re-examination of the WEEE recovery targets, on the possible setting of separate targets for WEEE to be prepared for re-use and on the re-examination of the method for the calculation of the recovery targets set out in Article 11(6) of Directive 2012/19/EU on WEEE, COM/2017/0173 final.

[229] In contrast to open and closed loops that only concern the technical process of recycling, a.k.a the efficiency of metal recovery via smelter or other process.

[230] JRC 2017, p. 16.

recovery currently is) and criticality are just some of the factors that must be considered when designing recovery targets.

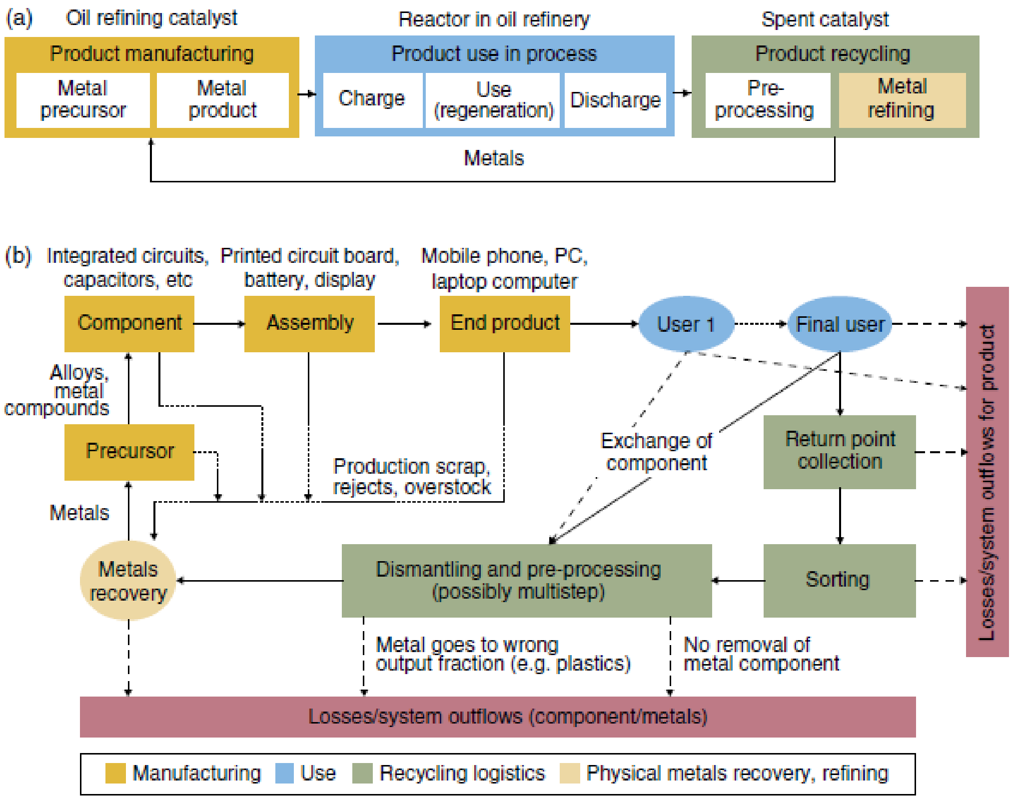

Figure 10: The differences in material flows of B2B industrial catalysts (closed loop) and customer goods (open loop).[231]

Another issue with flat recovery percentages would be that currently there is limited information available on the concentrations of CRMs in different electronic products[232], and accurate & comprehensive data on CRM concentrations would be essential for this solution. Therefore before this could be applied, it would be necessary to create monitoring methods and processes to track the amount of CRMs in EEE accurately enough so that recovery targets can be set.

[231] Hagelüken 2014, p. 59.
[232] See for example Perrine Chancerel et al., ”Data availability and the need for research to localize, quantify and recycle critical metals in information technology, telecommunication and consumer equipment”. Waste Management & Research 31(10) Supplement 3–16, 2013, p. 5, 10-11 and 14 (Table 4.). “An important finding of the assessment of the data is that reliable quantitative data are available for almost none of the applications using the selected critical metals in EEE. Even though some investigations report the results of their respective analyses, most research uses secondary data and theoretical metals based on assumptions to calculate the content of critical metals.”.

5.4.2. The importance of selective collection to maximize CRM recovery rates (move away from flat collection rates)

Currently, in WEEE recycling schemes CRM content of the products is not considered at all, as collection targets are flat percentages of products put on the market, which is essentially the same solution as with recycling targets.[233] In the current system, collection is a part of EPR, and EEE producers and importers generally outsource their collection responsibilities to collective schemes. The targets are flat and set across different product types. This, when combined with the recycling targets, means that the schemes will optimize their pre-processing to maximize the recyclability of major elements of the collected products[234] as there is no incentive for the collective schemes to consider the downstream recyclability of less common materials. In addition, these schemes do not currently function as intended in all EEE product categories, one of the major offenders being most customer small-scale electronics.

As discussed in the previous section, efficient collection of disposed customer products is difficult to achieve when compared to business-to-business machinery, due to the large user base and the easier disposability of the product. A prime example is mobile phones, which currently have a low collection rate: 12-15 % of them are estimated to be recycled in proper manner. In their context, the problems are "hibernation" (customers storing outdated and disused products at home) and export to non-EU countries.[235] In addition, collection rates are hindered by high mobility of products, multiple changes of ownership during product life cycle, and of the owners' lack of awareness both on the opportunities to recycle and the importance of doing so.[236] This leads to material dissipation even before the collection and recovery-phase of product life cycle, not to mention the losses that effective "landfill

[233] ERECON has noted the same issue in the context of rare earths. ERECON 2015, p. 60.
[234] *Ibid.*
[235] The European Economic and Social Committee, "Identifying the impact of the circular economy on the Fast-Moving Consumer Goods Industry: Opportunities and challenges for businesses, workers and consumers – mobile phones as an example". Centre for European Policy Studies, 2019, p. 7, 17-18, 23-24 and 32-33.
[236] United Nations Environment Programme (UNEP). Recycling Rates of Metals—A Status Report; A Report of the Working Group on the Global Metals Flows to the International Resource Panel. United Nations Environment Programme (UNEP): Nairobi, Kenya, 2011.

disposal" incurs, and as such showcases clearly the problems that open loop life cycles create for recycling.

Meanwhile, it has been shown that a targeted collection of CRM-rich products combined with CRM-focused pre-processing can significantly increase the recovery of CRMs down the recycling life cycle[237], and this is especially prominent in the category of small-scale customer electronics. Targeted collection of certain small-scale consumer products rich in CRMs, such as mobile phones, is effective because mixing of different WEEE types (e.g. mobile phones and electric tools), as discussed before, will cause difficulties further down the recycling cycle, as the mix of material becomes wider and less homogenous.[238] This showcases the need for higher-quality collection and pre-processing and the importance of increasing customer participation in collection programs.

However, it is less clear whether specific legislation is needed to achieve this – if specific CRM recovery targets are created via legislation, it can be expected that the quality of collection and pre-processing will increase, as this phase can be expected to contain "low-hanging fruits", meaning simple enhancements in process quality that would significantly enhance CRM recycling[239], and such legislation would incentivize producers and collective producer schemes to pluck those fruits, so to speak, in order to achieve those targets.[240] Incentivization of the producers is the key issue, and if such stimulus is given via regulatory means, they will devote more resources to solving issues such as consumer participation.[241] Too detailed regulation may prove counterproductive in this regard, as it could potentially stymie innovation. However, setting a collection and a pre-processing standard[242] that

[237] ECODOM, Recovery case study <http://www.criticalrawmaterialrecovery.eu/wp-content/uploads/2018/12/ECODOM-Recovery-case-study.pdf> (Accessed 26.3.2020.)
[238] For example, Hagelüken 2007, p. 2-3.
[239] As seen in the ECODOM case study, even the fairly simple task of sorting CRM-rich WEEE separately and sending the scrap to a facility that has the technology to extract CRMs will result in significant gains.
[240] One potential method of increasing collection rates is deposit schemes: it has proven to be very effective in the context of plastic bottles, and it is also showcased in the aforementioned example of Apple's recycling scheme, as customers are given credit to future purchases of Apple products.
[241] One example of successful incentivization is the PET plastic bottle collection system implemented in Finland: if the producer is a part of an efficient bottle recycing system, they will avoid a significant "packaging tax" on their products. The Finnish PET bottle recycling system has one of the highest recycling rates of such systems in the world. The take-back scheme utilized by Apple as mentioned in Section 5.3.2 is an excellent example of incentivized take-back scheme in the context of customer electronics.
[242] A list of currently existing ones: <https://ec.europa.eu/environment/waste/weee/standards_en.htm> (Accessed 28.3.2020)

focuses on these issues may be an option to consider in the future, if only for guidance's sake for the operators.

5.4.3. Summary

Current recovery targets do not promote anything other than the recovery of base metals that constitute most of the mass of electronic products, and it appears necessary that they must be supplemented via mandatory CRM recovery targets or some other form of incentivization that increases CRM recovery (such as eco-modulation, which is closely related to eco-design). However, flat CRM recovery targets would appear to be the simplest solution, though it would require first that the issue of limited product material data to be resolved[243] (though this applies to an extent to any possible solution).

In addition, one possibility for supplementing CRM recovery targets are requirements to use certain percentage of recovered CRMs in products. This would increase the demand for recycled material, and such suggestion has come up in stakeholder interviews.[244] This could be done via incentives and penalties imposed on products based on their recycled CRM content via revisions to the Ecodesign Directive (which is the focus of next section).

5.5. Creating ecodesign requirements to enhance recycling of CRMs

5.5.1. The Ecodesign Directive

Directive 2009/125/EC, or Ecodesign Directive currently sets the requirements for "ecodesign" within EU. Ecodesign, in a wider context, means that during the design phase of the product the complete environmental effects of the product are considered for its entire

[243] Cite note 232.
[244] SCRREEN D8.2, p. 30-31.

life cycle with the goal of minimizing its negative impacts.[245] This includes the end-of-life phase and so-called “Design for Recycling” -mode of thinking. The goal of Design for Recycling is to maximize the recoverability of materials from the end-of-life product and to keep the quality of the old material as high as possible.[246] However, Ecodesign Directive in its current form does not include such demands, and it is mainly focused on increasing the energy efficiency of products. This may change in the near(ish) future though with the new Ecodesign directive initiative, which is discussed in the next section.

An example of how product design can influence recyclability is to look at how accessible (or more accurately, removable) a component is. This can be illustrated by differences of recyclability in car catalysts and car electronics. Car catalysts (which contain PGMs) can easily be cut from the car’s exhaust system and sent to separate treatment. Meanwhile electronics tend to be distributed all over the vehicle’s frame and are therefore difficult to remove. Because of this the electronics are usually left in place as the frame is sent to a shredder, and in post-processing the CRMs of the electronics become mixed with the base metals of the frame and are eventually lost due to the aforementioned thermodynamic limitations that arise when many different metals are mixed together in the recycling process.[247] This leads to another possible example of how to implement Design for Recycling: avoiding, when possible, incompatible material combinations in the design of components.[248] In general, metallurgy aspects from recycling point of view should be one of the focus areas in the design of electronics.[249] These issues form a key area in which to expand towards the Ecodesign directive – from energy efficiency towards resource (or material) efficiency[250], especially in the context of CRMs (in addition of other metals).

[245] C. Luttropp and J. Lagerstedt, ‘EcoDesign and the Ten Golden Rules: generic advice for merging environmental aspects into product development’. 14 Journal of Cleaner Production, 2006, 1396–408.
[246] Beitz, W., “Designing for ease of recycling”. Journal of Engineering Design, 2007, 4(1), 11–23.
[247] Hagelüken 2007, p. 3.
[248] Hagelüken 2014, p. 55.
[249] For a general overview, Reuter, Markus & Matusewicz, Robert & Schaik, Antoinette, “Plenary Lecture: Lead, Zinc and their Minor Elements: Enablers of a Circular Economy”. World of Metallurgy – ERZMETALL, 68, 2015, p. 132-146.
[250] Examples of such proposals are in Bundgaard, Anja & Remmen, Arne & Zacho, Kristina, “The Ecodesign Directive 2.0 - from energy efficiency towards resource efficiency”, 2015, and C. Dalhammar et al., “Addressing resource efficiency through the Ecodesign Directive: a review of opportunities and barriers”, TemaNord *511*, Nordic Council of Ministers, 2014.

Ecodesigning electronic products for recycling is a complex task. Product design must accommodate mechanical pre-processing (component accessibility) and metallurgical processing (avoiding incompatible metal combinations) at the same time – and these parameters can change over time with advances in recycling technology. In terms of legislation, calculating “recyclability” in the context of electronics appears to be a very difficult task, though attempts have been made.[251] In addition, reaching high recyclability very likely demands active dialogue between producers and recycling actors in order to reach mutually effective solutions, or alternatively of the producer taking up some of the traditional roles of recycling actors, such as dismantling via in-house solutions (see section 5.3.2.). Legislation (or other policy actors) should look for ways to increase these.

However, if producers are mandated to reach certain CRM recycling rate targets, from it follows that they will have the incentive to work together with actors on the recycling side in order to fulfil their obligations in the most economically effective way. If regulation that necessitates higher quality recycling is introduced, it can be expected that many producers would look into eco-design as one of the pathways that can help them to reach those targets, and at least large companies would seek to create integrated solutions where they could directly control some aspects of the post-customer stage so that they could maximize the benefits of their eco-design efforts. Therefore mandatory eco-design requirements would likely work best if they are employed in a supporting role to the mandatory recovery targets and being “loose” enough to allow for innovative recycling solutions. As has been said, detailed regulation in this area appears difficult due to the problems related to calculating recyclability, so caution should be employed when considering possible mandatory recyclability requirements.

5.5.2. The new Ecodesign directive initiative of the new Circular Economy action plan

In the new Circular Economy action plan the EU has set new goals for the Ecodesign directive, with planned additions to improve, inter alia, product durability, reusability,

[251] For example J. Huisman, C. B. Boks; A. L. N. Stevels, “Quotes for environmentally weighted recyclability (QWERTY): Concept of describing product recyclability in terms of environmental value”. International Journal of Production Research, 41:16, 3649-3665, 2003.

upgradability and reparability, increasing their energy and resource efficiency, increasing recycled content in products, enabling remanufacturing and facilitating high-quality recycling.[252] Acknowledging the potential inherent in product design to enhance recycling is step towards the right direction, especially as the importance of high-quality recycling has been noted by the legislator, if concerns raised in the previous section are taken properly into account. When drafting the new Ecodesign directive, attention should be paid towards CRMs and the key issues that currently keep their recycling rate low. As has been said, what constitutes recyclability is a complex issue in the context of CRMs in WEEE, and defining it via legislation is difficult.[253] This is exacerbated by the fact that recycling technology is not static and new developments will allow for CRM recovery from streams and mixes where it previously was not possible.[254] Thus, the focus on recyclability should not take the current limitations for recyclability for completely granted, as that would stagnate innovation.

One ecodesign feature in the context of WEEE that has often came up in stakeholder interviews is the separability of different product components[255], especially of the ones that contain CRMs. However, as can be seen from the example of Apple and Daisy-robot, component separation can be achieved via original means. Based on this, it appears that measuring component separability via legislation could be difficult and possibly counterproductive.

A different, and possibly more efficient approach, could be to demand a certain percentage of new products to consist of recycled materials on a material-to-material basis, including CRMs. This, in turn, would incentivize producers to either collaborate with recyclers or to come up with their own solutions (such as a dismantling robot like Apple's Daisy) to ensure

[252] COM(2020) 98 final, p. 4.
[253] On the difficulty of measuring recyclability, see Maximilian Ueberschaar, *Assessing recycling strategies for critical raw materials in waste electrical and electronic equipment* (Doctoral Thesis, Technische Universität Berlin, 2017), p. 18-19. <https://depositonce.tu-berlin.de/handle/11303/6730> (Accessed 21.3.2020).
[254] Examples of new technologies that have the potential of creating new viable material mixes: Lahtinen, E., Hänninen, M. M., Kinnunen, K., Tuononen, H., Väisänen, A., Rissanen, K., & Haukka, M., "Porous 3D Printed Scavenger Filters for Selective Recovery of Precious Metals from Electronic Waste". Advanced Sustainable Systems, 2 (10), 2018; and Arda Işıldar, Eric D. van Hullebusch, Markus Lenz, Gijs Du Laing, Alessandra Marra, Alessandra Cesaro, Sandeep Panda, Ata Akcil, Mehmet Ali Kucuker, Kerstin Kuchta, "Biotechnological strategies for the recovery of valuable and critical raw materials from waste electrical and electronic equipment (WEEE) – A review". Journal of Hazardous Materials, Volume 362, 2019, p. 467-481.
[255] For example SCRREEN - D8.2, p. 31-32.

the recyclability of their products so that they can secure a supply of recycled CRMs, and increase the demand of recycled materials, making investments in recycling technologies and facilities more attractive. Such a requirement would fit perfectly in the scope and goals of the revised Ecodesign directive.

5.6 Enabling the shipments of waste and building a (global?) recycling network

The nature of CRM recycling from WEEE is defined by the (relative) low concentrations of the materials in the waste stream. For this reason, the recovery of several of these materials would not be economically viable (without significant advances in technology) with a high density of processing plants in one region, due to the fact that the initial cost of investment for such facilities is so large that handling only small streams would be completely unviable. Efficient treatment of these materials requires large, continental volumes of waste flows, and as such the most efficient operation for many rare materials would likely be one facility that handles all the WEEE containing that material of a large commercial area, such as EU, or possibly even on global scale.[256] Therefore in order to secure viable quantities of potential material, the formation of a some form of multinational network of CRM recycling should be considered, and in the centre of this is the efficient transport of shipments of waste containing these CRMs. The efficiency of current legislation for waste shipments been identified as a problem.[257] The problems stem from lack of uniformity in defining, implementing and applying existing waste regulations across Member States. The lack of harmony has resulted in significant paperwork requirements for transboundary waste shipments within and from outside the EU, and the bureaucratic drag hinders the flow of WEEE across member states.[258]

However, as illegal shipments of WEEE to non-compliant jurisdictions and treatment facilities is already a major problem, strengthening the enforcement of waste shipment regulation must be done at the same time. The combination of profitability (it is several times cheaper to illegally export WEEE to another jurisdiction with laxer standards) and poor enforcement with a low level of penalties are the main drivers of illegal WEEE exports –

[256] For example, Miliute-Plepiene; Youhanan 2019, p. 30.
[257] ERECON 2015, p. 61.
[258] Though as has been shown by CWIT project, the cumbersome formalities have not prevented illegal WEEE shipments. An open question is how much the bureaucratic burden increases the incentive of illegal shipments.

when penalties are low and simultaneously the risk of being caught is low, the end result is quite predictable. The enforcement problems are compounded by uneven level of resources that are given to enforcement agencies in different Member States. Also, the complex nature of WEEE as a waste stream lends itself to illegal shipments: it is easy to disguise, the field is comprised of many actors, and WEEE is produced in immense amounts – all these factors create opportunities for illegal activities.[259] While a lawyer's *learned scepticism about simple solutions for complex problems*[260] should not be forgotten, a simple change here would be to increase the penalties of illegal WEEE exports significantly: due to the nature of the field, achieving a comprehensive, all-encompassing surveillance of WEEE exports would likely be difficult to achieve and require a long time to develop. As illegal exporting is essentially a "rational" economic crime, increasing penalties would be a simple step to reduce the attractiveness of the option.[261] However, as criminology and penology are not and cannot be a focus in this thesis, detailed investigation of this issue must be left for future studies.

5.7. Summary of recommendations

A critical point is to recognize in legislation that WEEE is a rich source of Critical Raw Materials and that recovering those materials is important. Circularity concerns, material efficiency and recyclability must be added to the central goals of the legislation. At the centre of this is some form of requirement (strict flat recovery rate requirement or possibly "soft" eco-modulation economical incentivization) to recover CRMs from the waste – as discussed in section 3, the demand and use for many of these materials is rising so rapidly that developing recovery processes for them is essential, considering the current importance given to Circular Economy in EU policy. However, further research is required in order to design effective legislation, as the issues involved are complex, merging economic and technological problems.

[259] Geeraerts, K., Illes A. and J-P Schweizer, "Illegal shipment of e-waste from the EU – A case study on illegal e-waste export from the EU to China". European Union Action to Fight Environmental Crime (EFFACE), 2015, Chapter 4.8: Motivations and drivers behind the illegal export of WEEE and p. 42.

[260] Cite note 36.

[261] As per the maxim of Gary Becker: "[A] person commits an offense if the expected utility to him exceeds the utility he could get by using his time and other resources at other activities." Becker, Gary S., "Crime and Punishment: An Economic Approach." Journal of Political Economy, vol. 76, no. 2, 1968, pp. 169–217.

In addition with CRM recovery targets, maintaining their recyclability before the recycling phase should be supported via legislation in the key parts of EEE life cycle, and this legislation should at the least include the collection phase and pre-treatment before actual material recovery. In those phases, maintaining necessary separation of products, components and different materials is essential to ensure the recoverability of CRMs. These requirements should closely follow the current status of recovery technology and carefully avoid stagnating innovation, as advances there can reduce the requirements for pre-treatment over time. It is important to recognize that solutions such as targeted collection of CRM-rich products and high-quality pre-treatment are not the end goal, material efficiency is, and therefore they are only supporting goals that should be re-evaluated in consistent intervals. Eco-design plays a similar role: it can significantly help material efficiency and recyclability, but what constitutes recyclability is dependant on current recycling technology and processes, so therefore eco-design requirements must be fluid enough to support novel recycling approaches.

The electronic product life cycle, from recycling point of view, could be summarized as thus: Product design and manufacture -> Customer use -> Collection after disposal -> Pre-treatment before recovery -> Material recovery -> Returning recovered materials back to economy (back to the first phase, “closing the loop”). Legislation can support Circular Economy of CRMs (and other materials as well) in all these phases if it chooses to do so, though the most efficient “level of detail” of mandatory requirements remains to a degree an open question: if the central goal, high CRM recovery rates, is made mandatory, exactly how much regulatory support would it need? How much can the actors in the field be trusted to develop innovative approaches and standards to achieve that goal? Will “micromanagement” be necessary, or will the different industries come up with more efficient solutions if they’re given the freedom to look for them? These questions point towards the view that it would perhaps be better to start with basic target of CRM recovery rates, possibly supplemented by some targeted collection requirements, and then adjust over time to target the bottlenecks that may arise. However, such approach would require resources for monitoring the development of industry and to develop new legislation in a relatively agile way, and it remains to be seen how much the EU and its Member States will be willing to commit to increasing the recovery rates of WEEE – so far, as the age of the legislation and the problems of its enforcement show, the issue has somewhat been on a back-burner in recent years.

6. Conclusions

In conclusion, the answer to the first research question, “how and why the current EU legislation on WEEE does not facilitate the recycling of CRMs?”, can be summarized thus: the main points of the legislation have been built around waste management issues of the previous generation of environmental policy, namely reducing the landfilling of waste and elimination of hazardous substances. It does not (as of yet) properly target the current-day concerns of circularity, material efficiency and material criticality. As such, it can be considered outdated and in need of revision, which it may well get in the next few years, as the EU strives toward goals set in its New Circular Economy Action Plan and Green Deal.

The answer to the second research question, “what key issues the legislator should pay attention to in order to facilitate Circular Economy more effectively, especially in the context of CRMs?“, is more difficult to answer, but some progress has been made. All-in-all, as has been repeated several times, the recycling phase of WEEE is only the final link in a long product life cycle (in terms of number of phases, not time), and in the context of material efficiency, all the stages are intertwined. Legislation must recognize and reflect that fact and attempt to support material efficiency in all those phases. A simple flat recovery target for different CRMs would likely go a long way (on paper) in increasing recovery rates, but it may not be enough by itself if it is not supported by other regulation and policy, such as eco-design and collection standards and other reinforcement for a circular economic ecosystem of electronics. Further research is needed in the key issues identified in this thesis in order to create effective and robust legislation that furthers Circular Economy goals effectively without stifling innovation. In addition, regulatory changes will not be enough if significant investments to enforcement, monitoring and oversight are not made. In some ways, electronics recycling is currently a “wild west” of sorts: legislation is immature and enforcement is incomplete.

In order to reach high recycling rates for CRMs, the entire mindset around the recycling of WEEE needs to be adjusted. Currently the main goal effectively is to recycle as high a percentage of the total mass of the waste stream as possible, which is based on antiquated concerns around limited landfill capacity[262] and designed for mono-substance waste streams[263], which does not suit the optimal recycling of modern complex electronic products that contain many important materials in small concentrations. The central theme of current EU industrial strategy, Circular Economy, is currently almost completely ignored in the legislation, as the legislation has been designed before Circular Economy came to the forefront of EU policy. The revision of WEEE Directive requires a true circular economy mindset that recognizes the unique nature and challenges of WEEE as a waste stream in a holistic manner. It is critical to recognize that WEEE contains small concentrations of extremely valuable materials that will not be recovered within the current legislative framework because the legislation ignores their importance (in the context of WEEE recycling). In addition, the current legislative framework also misses the fact that the environmental impact of different metals differ from one another, which also speaks against the use of recycling targets based on a percentage of total mass of the waste stream.

Also, the importance of constant surveillance of technological developments cannot be understated. The importance is twofold: first, as mentioned previously, WEEE recycling technology is not static – new technologies can introduce new recycling methods, and legislation must take this into account, especially by not inadvertently causing such technology to either not develop or make it economically ineffective due to misplaced responsibilities placed on actors. In addition, constant review of the effectiveness of the legislation is key.[264] As data is accumulates over time, policy must respond to new information and developments from the field.

The changes and new legislation required to facilitate high-level CRM recycling from WEEE would be ambitious and they would change the field of EPR significantly. However, the EU already has a history of ambitious, impactful legislative projects (such as GDPR). As noted in the communication on the Green Deal, it takes 25 years to transform an industrial sector and all the value chains that it is connected to, and for that reason if Circular Economy targets are to be reached in 2050, decisions and actions need to be taken in the next five years.[265] The electronics sector (especially customer electronics) requires a life cycle

[262] van Ewijk; Stegemann 2016.
[263] Hagelüken 2014, p. 48.
[264] "Good legal policy also requires serious ex post evaluation studies to examine whether a particular instrument or policy was indeed able to achieve the goals expected by the legislator." Faure 2012, p. 31.
[265] COM(2019) 640 final, p. 7.

overhaul if large-scale CRM recycling is to be achieved in order to lessen the dependency on virgin raw material and reducing their use in linear economy manner. WEEE legislation must be revised in order to facilitate this change quickly and effectively.